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SUMMARY

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The Origin of Angle-Geometry

I. Introductory. Geometry of Lines and Geometry of Angles.

1. — *Ambiguity of the Terms.*

There is a great deal of ambiguity and lack of clearness in the use of the terms line-geometry, angle-geometry, (1) and trigonometry. It is, however, a good old habit, among mathematicians in particular, to commence their treatises by giving clear definitions of the terms to be employed. In following this example the writer desires to set forth at the outset the sense and meaning in which he is going to use these words in the subsequent discussion.

2. — *Geometry of Lines and Geometry of Angles.*

Under geometry of lines this phase of geometry will be understood where *lines only*, not angles, are used for purposes of mensuration. In the beginning, of course, the lines are the sole *objects of mensuration*. Later on, with the progress of civilization, people proceeded to measure surface and solids; but even then, lines were the sole *means of mensuration*, areas and volumes being measured by their help. The sides, the length and breadth, the base and perpendicular, the diagonals, and the diameter and circumference are considered both as objects and means of mensuration, but no cognizance is taken of angles. It is very likely that there is a tacit addition and a subconcious understanding that the figures are rectangular, but this is never expressly mentioned or clearly stated. When the human mind first realizes the importance of angles, formulating in a distinct and scientific manner definitions, classifications and theorems relating to them,

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(1) Some prefer the word *goniometry*. This word was first used by Thomas Fantel de Lagny (*c.* 1710); see Smith, *History of Mathematics*, II, p. 612.

and using them as objects and means of mensuration, then a new stage of mathematics is inaugurated, *the geometry of angles*.

3. — *The Geometry of Angles. Angle-Geometry and Trigonometry.*

In general historians of mathematics use the words trigonometry and angle-geometry promiscuously to indicate any kind of geometry of angles. In this discussion, however, it seems convenient to distinguish between a geometry of angles where the angles are the *object of mensuration* and another kind of geometry where the angles are also used as a *means of mensuration*, to ascertain the length of the sides, or the areas and volumes of figures. Angle geometry and trigonometry will be used as two different terms for these two different conceptions. Under angle-geometry this branch will be understood where angles are primarily the object of mensuration and comparison, while trigonometry will be used to signify this large field of geometry where angles are primarily the means of mensuration. Trigonometry is a well established term, universally used to mean this branch of mathematics which deals with the ratios of the sides as certain functions of an angle (sine, cosine, etc.) (2).

The term « angle-geometry » will be used in this paper to signify all those theorems and propositions, relating to angles and to the theory of angles, which are not contained in the science of trigonometry. For example, it will include the definition of angles and parallels (3) ; the classification of angles into right and oblique, acute and obtuse; theorems on the equality of right angles, or of oblique angles in the isosceles and equilateral triangles, in parallelograms, etc. ; propositions

(2) It was fitly discussed by D. E. SMITH (*History*, II, p. 600) as follows : « If we take trigonometry to mean the analytic science now studied under this name, we might properly place its origin in the 17th century, after the development of a satisfactory algebraic symbolism. If we take it to mean the geometric adjunct to astronomy in which certain functions of an angle are used, we might look for its real origin in the works of HIPPARCHUS (c. 140 B. C.), although there are earlier traces of its use. If we take it to mean literally « Triangle measurement » the origin would naturally be placed much earlier, say in the second or third millennium B. C. Since this third phase is considered under geometry, we may properly confine our work to the development of the idea of the functions of an Angle ».

(3) Parallels being understood as straight lines in a plane, but not forming an angle.

on the sum of the angles in a triangle or polygon, on the angles in the semicircle, or with their vertices anywhere on the circumference or at the centre. In short all the theory of angles which constitues the subject-matter of most of *Books* I-III, IV, VI, and XI of EUCLID, and which together with the theory of proportions might be declared as the foundation of the scientific geometry of the *Elements*. Trigonometry like the geometry of lines was a practical science (**), an adjunct of astronomy and mensuration (*geodesy*); whereas angle-geometry was an abstract science, one of the foundations of the theory of geometry.

II. THE ORIGIN OF ANGLE-GEOMETRY. ANGLE-GEOMETRY AMONG EGYPTIANS, BABYLONIANS AND GREEKS.

4. — *Greek tradition. Greek origin.*

The question as to who were the founders of angle-geometry receives a clear answer from Greek tradition. The Greek historians of mathematics EUDEMUS (c. 335 B. C.) and PROCLUS (c. 410-485 C. E.) (4) name THALES as the inventor of the following propositions: (1) The angles at the base of an isosceles triangle are equal; (2) When two lines intersect, the vertical angles are equal; (3) Two triangles are congruent, if they have two angles and a side respectively equal; (4) An angle in a semicircle is a right angle. After THALES the theory of angle mensuration was further developed by the Pythagoreans. « The Pythagoreans, before... 450 B. C., had practically completed the subject-matter of Books I, II, IV, V, (and perhaps III) of EUCLID's *Elements* » (5).

5. — *The modern historians. Egyptian origin advocated by German school.*

In contrast with the clear statement of Greek tradition some of the modern historians of mathematics would like to credit

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** The editor does not agree with this. Trigonometry is neither less theoretical nor more practical than any other branch of mathematics; it all depends upon one's understanding of it (G. S.)

(4) Cf. HEATH, *Greek Mathematics* I, p. 130; SMITH, *History*, I, p. 67; CANTOR, *Geschichte der Mathematik*, I, 4th ed., pp. 135 *seqq.*

(5) HEATH, *Greek Mathematics*, I, p. 2.

the ancient Egyptians, or also the Babylonians, with the knowledge of those theorems. The German historians, in particular, show this tendency to antedate many of the Greek inventions and to ascribe them to the Egyptians and Babylonians. C. A. BRETSCHNEIDER, one of the first to represent this theory, says : (6) « Dass gerade diese sogenannte ionische Schule in der Geometrie nur mässiges geleistet, im Allgemeinen sich nur darauf beschränkt hat, das aus Ägypten überkommene zu erhalten und weiter zu geben. Wir können daher *mit Zuversicht behaupten* (7), dass die getrennte Beweisführung fur die Winkelsumme im gleichseitigen, gleichschenklingen und ungleichseitigen Dreiecke noch aus der ägyptischen Geometry stammt. » Then he continues : (8) « Aus dem Rhind'schen Papyrus scheint so viel *mit Sicherheit* hervorzugehen, das die Lehre von den Winkeln und Parallellinien... der Hauptsache nach von den ägyptischen Goemetern entwickelt und durch *bündige Beweise* festgestellt waren. » According to BRETSCHNEIDER (9) all the geometric discoveries of THALES, and also his measurement of the pyramids by the shadow and his ascertaining of the distance of the boats from the sea shore are of Egyptian origin. He even goes so far as to say (10) : « Es scheint sogar, als ob die Lehre von der *Flächenvergleichung und Messung*, die die Ägypter..... bereits in ziemlichem Grade ausgebildet hatten, dem THALES und seinen Schülern, wenn auch nicht geradezu unbekannt, doch wenig geläufig gewesen sei. Denn alle Probleme, die uns innerhalb dieses ersten Jahrhunderts der Griechischen Geometrie genannt werden, bezichen sich ganz ausschiesslich auf *Construction und Messung von Linien*; es ist kein einziges bekannt, was einen Flächeninhalt beträfe. Würde es nun auch vereilig sein, daraus den Schluss zu zichen, dass THALES in seinen geometrischen Studien bei den Ägyptern garnicht bis zur Messung und Vergleichung des Flächeninhaltes ebener Figuren gelangt sei (eine Annahme, die an sich gar nichts unwahrscheinliches hat), so möchte doch wenigstens so viel daraus folgen, dass er sowohl wie seine Schüler gerade diesem Teile der Planimetrie keine besondere Aufmerksamkeit zugewendet

(6) *Die Geometrie und die Geometer vor Euklides*, 1870, p. 15.
(7) These and the following italics are due to the present writer.
(8) *Ib.*, p. 17.
(9) *Ib.*, pp. 42 and 44.
(10) *Ib.*, pp. 66-67.

haben. » BRETSCHNEIDER thus, with a great deal of « buts and ifs » intimates that THALES, the disciple of the Egyptians, and with him his school, did not proceed as far as to the *mensuration of areas* and their comparison, but, as a kind of dull and backward pupil of the Egyptian school remained behind in the lower field of construction and *mensuration of lines*. And were we to follow RÖTH, so BRETSCHNEIDER points out (11), then nearly all that the Greeks before EUCLID accomplished was Egyptian property. It seems indeed that BRETSCHNEIDER is influenced, to a certain extent, by the philosopher RÖTH who undertook it with great force (12) to prove that all the early Greek achievements in science and philosophy go back to Egyptian sources.

This theory of RÖTH, as it seems, exercised a great and lasting influence upon the German historians of mathematics. HANKEL (13) believes that the propositions attributed to THALES and OENOPIDES (c. 465 B. C.) are of Egyptian origin. « There is *no doubt* about it », he writes, « that OENOPIDES learned his constructions from the Egyptians ».

CANTOR (14) summarizes the divergent opinions as follows : « So kam es, dass dem einen bewiesen schien, die Ägypter hätten von Winkeln nichts gewusst, und THALES sei der erste gewesen, der eine Winkelgeometrie ersann. (15) Dass ein zweiter ein Verdienst des THALES darin fand, dass er eine Liniengeometrie in dem Sinne schuf, dass er das Verhältnis der Linien einer Figur ins Auge fasste, während den Ägyptern nur die praktische Geometrie der Flächenausmessung bekannt gewesen sei, (16) dass

(11) *Ib.*, p. 18. See also the Preface *ib.*

(12) In his *Geschichte unserer abendländischen Philosophie*, 2nd vol., 2nd ed. Mannheim, 1862.

(13) *Zur Geschichte der Mathematik*, 1874, pp. 91-92.

(14) I, 4th ed., p. 139.

(15) CANTOR does not quote the sources nor does he mention the authors by name. The sources of this theory are unknown to the writer.

(16) This is the theory of ALLMAN, G. J.; see his *Greek Geometry from Thales to Euclid*, 1889, pp. 7-8 and note *ib.* It was also adopted by SMITH, *History*, I, p. 68. Under « line-geometry » these authors seem to understand something similar to trigonometry or angle-geometry, at any rate something higher than mere mensuration of areas. It is interesting to note that BRETSCHNEIDER, who was the first to use the phrase « geometry of lines » (*loc. cit*, pp. 66-67, quoted above) gave it another meaning. According to BRETSCHNEIDER, « geometry of lines » is something lower, more elementary than mensuration and the comparison of areas. ALLMAN was well acquainted with BRETSCHNEIDER's work,

ein dritter nicht Anstand nahm THALES und die älteren Griechen überhapt fast jeden Erfinderrechtes für verlustig zu erklären und ihr ganzes geometrisches Wissen für Ägypten zuruckzufordern (17); dass ein vierter an die entgegengesetzte Grenze streifend es für gleichgültig hielt, ob THALES überhaupt Ägypten besucht habe oder nicht, weil er Geometrisches in nennenswerter Menge von dort nicht habe mitbringen können » (18). CANTOR, himself, is inclined to adopt a theory corresponding to the third view with certain modifications. He credits the Egyptians with the knowledge of those propositions which Greek tradition ascribes to THALES and the early Pythogoreans. He attributes to the Egyptians the theorems on the equality of the angles at the base of the isosceles triangle and on the bisection of the circle by the diameter. He sees in the *seqt* exercices of the Egyptians a « theory of proportions » or a « chapter in trigonometry », and he believes in general that the whole difference between Greek and Egyptian geometry lay only in the method. The Egyptians used the inductive method, while the Greeks introduced the deductive method (19). In the same way CANTOR likes to credit the ancient Babylonians with a considerable amount of geometric knowledge. The Babylonians, in CANTOR's opinion, knew of parallel lines and of the radius, of the division of the circle into six parts by applying the radius as a chord; they knew of the 360 degrees of the circle and of angle degrees (20).

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which he highly esteemed (*Greek Geometry*, pp. 1-2 note). He took up the phrase « geometry of lines » apparently in deference to BRETSCHNEIDER, but employed it with quite a different meaning as something more advanced and more abstract than the Egyptian mensuration of areas. ALLMAN, *loc. cit.*, p. 7, points out: « THALES brought with him from that country (Egypt) the knowledge of Geometry and astronomy. He added the capital creation of the geometry of lines, which was essentially abstract in its character. The only geometry known to the Egyptian priests was that of surfaces, together with a sketch of that of solids... THALES, on the other hand, introduced *abstract* geometry, the object of which is to establish precise *relations*, between the different parts of figure, so that some of them could be found by means of others in a manner strictly rigourous. » In this sense of the term « geometry of lines » his theory comes much nearer to the truth. For the sake of clearness and precision, however, the writer thought it more apt to use the terms « geometry of lines » and « angle-Geometry » in a different way.

(17) This probably refers to RÖTH.

(18) Author unknown to this writer.

(19) CANTOR, I, 4th ed., pp. 109, 112-113, 140.

(20) CANTOR, I, 4th ed., pp. 45-47, 50.

In the footsteps of CANTOR follows TROPFKE. The theory of the qualities of parallel lines, the construction of the regular hexagon and various propositions of the theory of the circle and the triangle have their origin in Babylonian mathematics (21).

EUCLID's definition of the perpendicular (22), the division of angles into right, acute and obtuse, and the theorem of the equality of the vertical angles are to be traced to Egyptian origin (23).

Thus we might properly speak of a scientific tradition, represented mainly by the German school of RÖTH, BRETSCHNEIDER, HANKEL, CANTOR and TROPFKE, which is opposed to the Greek tradition and teaches the Oriental origin of Greek geometry.

6. — *Refutation in general.*

The fact, however, is that this tradition is mostly based upon vague conjectures and generalizations. In the mathematical documents of the Egyptians and Babylonians there is no evidence whatever to support it. There is no mention made of a theory of angles or of a mensuration of angles in Egyptian or Babylonian mathematics. There are even no terms for right and oblique angles, and the Egyptian word for the angle, *Knbt*, seems rather to signify a « corner » or « gate » (24) and not an angle, as a measurable quantity, in the modern or Greek sense of the word. No attempt is made to set up an equality between oblique angles, and even the equality of right angles is not expressly mentioned. Nothing is said about the postulate that the sides of the squares and rectangles, or that the altitude and the base form a right angle. The Egyptian formula for the area of the isosceles triangle is $\frac{b\,a}{2}$, where b is the base and a is one of the equal sides. The formula for the trapezium is $a.\ \frac{b_1 + b_2}{2}$ where $b_1 + b_2$ are the two parallel lines, and a is one of the sides. Here they take the side forming an oblique angle instead of the perpendicular forming a right angle. Thus we might properly speak of direct

(21) TROPFKE, IV, second ed., p. 4.
(22) *Book* I, def. 10.
(23) TROPFKE, IV, 2nd ed., pp. 48, 50-51.
(24) See hereafter, § 7, note of A. B. CHACE.

evidence for the statement that the Egyptians did not distinguish between right and oblique angles, or rather that they often neglected the difference between them. This is also the opinion of HERMANN SCHNEIDER, in his new book *Die Kulturleistungen der Menschheit*, p. 64, that the Egyptian did not discover the idea of the height.

Not being familiar with Egyptian language and hieroglyphics, and drawing his knowledge only from modern translations of and treatises on Egyptian mathematics, the writer thought it fit to ask an authority on Egyptian language and mathematics for information. After this article was written some of its findings and results were submitted to Chancellor A. B. CHACE, the latest editor of the Rhind Mathematical Papyrus, who devoted many years to the study of Egyptian language and mathematics, with the request that he would advise the author on their admissibility. Dr. CHACE was kind enough to send the subsequent note for which the writer wishes to express his deep appreciation.

7. — *Note of Chancellor* A. B. CHACE.

« I do not think that they had any conception of an angle as a thing to be measured, and it may be not even of one angle as being larger or smaller than another. In the building of a pyramid each layer of stone was set back a certain amount; that is what « seked » means. The word « ifd » means four. Applied to structures, or pieces of land, it may mean having four sides or it may mean having four corners. They had the idea of height written with a man holding up his hands), but we can think of a line measuring height as drawn upwards without thinking of it as forming a right angle with anything, and so, even if « *merit* » did mean altitude, or if the triangles of the Rhind papyrus were right triangles (halves of rectangles), it would not mean that they had a conception of angles and angle-measurement.

Of course there may be evidence of the idea of angle in Egyptian writings yet to be discovered, but so far as I know now they did not have it. »

8. — *The Seqt.*

All that we know about the so called *seqt* or *sqd* of the Egyp-

tians (25) is that it is a ratio between two lines of the pyramid, but we have not yet a certain knowledge of the nature of these lines, and of the use that was made of this ratio. So far we know that one of the lines was in vertical direction, forming the height, slant height or edge of the pyramid, and that the other one was in horizontal direction forming the half side or half diagonal of the base. The most probable theory is that advocated by REVILLOUT (26) and BORCHARDT (27) that the *sqd* is the ratio between half the side of the base ($\frac{b}{2}$) and the height of the pyramid (h); or in modern terms the cotangent of the angle of the slope. The pyramids were built in decreasing layers or stories of stones. In order to obtain an even slope and a smooth surface in filling out the corners the inlaying stones must have the same slope or the same ratio between the base and the height. This was in all likelihood the *seqt* (28). But it would be a great mistake to assume that the ancient Egyptians actually measured angles or computed their cotangents. They only had the practical rule and some vague idea, as all the primitive people engaged in building would have, that the slope of a pyramid is determined by the ratio of half the side of the base to the height.

9. — *Instinct and Consciousness, Intuition and Science.*

CANTOR, however, conceives of the *seqt* as a method to measure the abstract angle, and, since we have the choice to take the one or the other half of the side of the base, he further draws the conclusion that the equality of the angles at the base of the isosceles triangle ***doubtless must*** have been known to the Egyptians (29). In a similar way he credits the Egyptians with the knowledge of the bisection of the circle by the diameter, and the Babylonians with the knowledge of the qualities of parallel lines, basing his belief upon the evidence of certain Egyptian wall-pictures showing a circle divided into many equal parts, and of certain drawings

(25) See the *Rhind Mathematical Papyrus*, problems, N° 56-60, ed. PEET, pp. 97-102; ed. CHACE, pp. 37-38, 154; CANTOR, I, 4th ed., pp. 99 *seq*; HEATH, *Greek Mathematics*, I, pp. 126 *seq.*; SMITH, *History*, II, pp. 600 *seq.*; 619, note 3; TROPFKE V, 2nd ed., p. 4; IV, 2nd ed., p. 155.

(26) In *Revue Egyptologique*, II, pp. 308, seqq.

(27) *Zeitschrift für ägyptische Sprache*, XXXI, (1893), pp. 9-17.

(28) See CANTOR, I, 4th ed., p. 100; TROPFKE, PEET and CHACE, *loc. cit.*

(29) I, 4th ed., pp. 139-140.

of two parallel lines on a Babylonian inscription. (30) By such a procedure we could perhaps credit Egypt and Babylon with the content of all the thirteen books of EUCLID's *Elements*. Furthermore, we know « that the bees built their hexagonal wax cells according to the laws of maxima and minima, that the birds observe the principle of symmetry in the structure of their nests », and " that no animal is so foolish as to follow a curved instead of a straight line between two points in its path " (31). Are we going to credit the bees with the *knowledge* of the differential calculus or the animals with the *definition* of the straight line as the shortest path between two points? Men were thinking and reasoning logically many thousands of years before they had the slightest idea of the science of logic, they were computing correctly before they knew of the common notions of EUCLID, they built their tents with two equal sticks on both sides having an equal inclination (32) before they had the slightest idea of angle-measurement or of the theorem of the equality of the angles at the base of the isosceles triangle, and in the same way it was also that the Egyptians built their great pyramids.

The theory of parallelism is closely connected with angle-geometry. But there is not the slightest trace of the knowledge of such things among the Babylonians (33). CANTOR thinks that the Babylonians knew the radius and recognised the rule that the radius drawn six times as a chord would give the inscribed regular hexagon, and that this was the reason that they took $\pi = 3$. In the writer's opinion, however, the fact that they took $\pi = 3$ proves to the contrary. If they would know that $6\ r = 3\ d$ is the perimeter of the inscribed hexagon they certainly would not identify this perimeter with the circumference of the circle and the arc of 60 with its chord against the clear evidence from sense perception. Apart from this, such concepts as the centre and radius of a circle were entirely unknown to the Egyptians, Babylonians and Hebrews ; They had no words for them,

(30) *Ib.* pp. 140, 109, 50, 46.

(31) SMITH, *History*, *I*, p. 5.

(32) See HANKEL, *Zur Geschichte der Mathematik*, p. 90.

(33) MEISSNER B., *Babylonien und Assyrien*, vol. 2, (1925), pp. 389-394, gives a complete summary of Babylonian geometry. But he knows nothing of angle-geometry.

and even the Greeks had no special term for the radius (34 .

10. — *Historic and Prehistoric Phases in Mathematics.*

It is interesting to note that CANTOR (35), himself, laid down the principle that the real history of mathematics commences, for him, with the first written documents relating to computation and to the comparison of geometric figures, and that it is not his intention to begin, like the historians of mathematics from the former centuries, with the creation of the world. In the course of his investigations, as it seems, he soon realized the importance of the prehistoric phase in mathematics, and found himself compelled to deviate from his principle and to include some of the manifestations of the earliest stages of the arts and crafts; a procedure which, as we have seen, created some confusion. It seems, therefore, more appropriate and consistent to devote a chapter or two in the beginning to the prehistoric stage of mathematics, a method adopted by DAVID EUGENE SMITH in his *History of Mathematics*. Here the mathematical laws as manifested in the cosmos, in the organic and animal life of the earth may be discussed. Here belongs also the prescientific phase of mathematics as it is developed in architecture and decorative art, in religious mysticism and ritualism, and in commerce and the observation of stars.

11. — *The Origin of the Geometry of Lines and Geometry of Angles.*

All we possibly may claim for the Babylonians and for the Egyptians are some practical rules of a primitive trigonometry. There is definite proof that the ancient Babylonians and Egyptians had the *gnomon* or sun-dial and also some primitive astrolabe.

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(34) The Hebrew word for the centre *mirkaz* is of Arabic origin. It cannot be older than the ninth century. There is also a Hebrew word *muṣṣaq* for the centre; it was used mostly by IBN EZRA; see the Hebrew Dictionary of BEN JEHUDA, VI, p. 2859. (BEN JEHUDA, *ib.*, did not understand that the word in SAVASORDA's *Ḥibbûr ha-Meshîḥah* means a « conic figure ». BEN JEHUDA's explanation of the word « *ṣûrâ thîsbartîth shawâ ha-ṣela'ôth* » is meaningless). The word *mirkaz* and the idea of the centre are not found in the geometry of AL-KHOWÂRIZMÎ (c. 820), which forms a special chapter (*Bâb al Misâḥah*) of his algebra... For the history of the word *radius* see TROPFKE, *IV* 2, p. 106 seq, and SMITH, *History*, *II*, p. 278.

(35) I, 4th ed., p. 16.

Some trigonometric rules might have been known and used for the shadow reckoning and the observation of the stars. On their cuneiform tablets of the time short before HIPPARCHUS (c. 150 B. C.) astronomical data have been discovered which are more exact than those given by the latter (36).

Thus we might be justified in saying that the *geometry of lines*, as a practical science, originated among the Babylonians and Egyptians. They accomplished the mensuration of areas and solids with the help of lines only. In *trigonometry* too, as a practical science, we might perhaps look for its earliest traces, its prehistoric phase, to the Egyptians and Babylonians. While *angle-geometry*, as an abstract science, is of Greek origin. THALES introduced the abstract *geometry of angles*, which in turn gave rise to a more advanced, scientific trigonometry, using the angles in addition to the lines for the purposes of mensuration and astronomy.

Trigonometry as a practical science, was further developed by the Hindus and Arabs in the Middle Ages, (37) while the abstract angle-geometry hardly received any further development through the Oriental races, being confined, up to the modern times, almost exclusively to the achievements of the ancient Greeks.

The Greeks frankly acknowledged the fact that the Egyptians were the founders of arithmetic and geometry in general (38). There is no reason to doubt the truth of Greek tradition when it claims one branch, the angle-geometry, as their invention and as their own field and dominion. Indeed nothing was more congenial to the Greek spirit than the angle-geometry which is the very foundation of the abstract and logical system of Greek mathematics. Apparently it is not a mere coincidence that EUDEMUS (c. 335 B. C.), the first historian of Greek mathematics, attached so much importance to this subject. He wrote a book *On the Angle*, and most of the fragments preserved from his

(36) See SMITH, *History*, *I*, p. 49; *II*, p. 351, 600; WEIDNER, E. F., *Handbuch der Babyl. Astronomie, Lieferung I* p. 62, TROPFKE, *V*, 2nd ed., p. 12; L. BORCHARDT *Altägyptische Zeitmessung* pp. 27 seqq. (on the gnomon), 54 (on dioptra).

Cf. however, BORCHARDT, *ib.*, p. 34, denying that the Egyptians had any knowledge of even the simplest trigonometric computations. « da wir auch einfache trigonometrische Rechnungen bei den alten Ägyptern nicht als bekannt voraussetzen dürfen. »

(37) Compare also CARL SCHOY, *Die trigonometrischen Lehren des.... Al-Bīrūnī*, Hannover, 1927, and the review by TROPFKE in *Islam*, XVII (1928), pp. 299-300.

(38) See the numerous passages quoted by CANTOR I, 4th ed., pp. 86, 102-103.

history of mathematics discuss the origin of theorems of angle geometry (39).

With the change of one word only (40) the writer would like to conclude this chapter with the fitting words of D. E. SMITH (41). « In the history of mathematics, as in the history of civilization in general, it is the setting forth of a great idea that counts... The great contribution of THALES lay in suggesting a *geometry of ‚angles'* and in making the subject abstract... Without THALES there would not have been a PYTHAGORAS,... and without PYTHAGORAS there would not have been a PLATO. »

III. THE ANGLE-GEOMETRY AMONG THE HEBREWS AND ARABS.

12. — *The Mishnath ha-Middoth* (42) *and the Geometry of* AL-KHOWÂRISMÎ (c. 825) (43).

The *Mishnath ha-Middoth* does not show the knowledge of angle-geometry that the Greeks possessed, but apparently it shows more than the Egyptians had. Thus the *Mishnath ha-Middoth* represents, in a certain sense (44) a phase of transition from Egyptian to Greek geometry. All that the *Mishnath ha-Middoth* contains about angles is that there are right (45) and oblique angles,

(39) See HEATH, *Euclid*, I, pp 34, 38, 181, 294, 296.

(40) « Geometry of angles » instead of « geometry of lines. »

(41) *History*, I, p. 68.

(42) This is the oldest Hebrew geometry (c. 150 C. E.). The writer has already had occasion to refer to this ancient treatise in *The American Mathematical Monthly*, vol. 33, pp. 263 note 5; and vol. 34, p. 81, note 3, and to give his view concerning the time in which it was written. A recent investigation which is to be published soon as an introduction to a new edition of the *Mishnath ha-Middoth* being prepared by the writer for the publications of The Alexander Kohut Memorial Foundation, has confirmed his conviction and will furnish evidence that the *Mishnath ha-Middoth* was written about 150 C. E. by RABBI NEḤEMYAH, the famous teacher of the Mishnah. This introduction will soon appear in the *Hebrew Union College Annual*, vol. 6, 1929.

(43) The earliest Arabic geometry, so far as known, is the so-called *Bâb al-Misâḥah*, « the chapter on mensuration », as it appears in AL-KHOWÂRISMÎ's *Algebra*, ed. ROSEN, London, 1831; Arabic text, pp. 50-64; English translation, pp. 70-85. It is almost a verbal translation of the *Mishnath ha-Middoth*. Anything said about the *Mishnath ha-Middoth* will therefore apply to AL-KHOWÂRISMÎ's geometry, unless otherwise stated.

(44) As far as the stage of its knowledge is concerned, but not in regard to the time of its origin.

(45) They are called « upright » angles; see hereafter.

and that the latter are divided into acute and obtuse, also called narrow and broad angles. (46) It also infers that all right angles are equal, though this is not expressly stated. It defines square and rectangle merely as having equal angles, without saying that they are right angles. (47) The third chapter of the *Mishnath ha-Middoth* is devoted to definitions and propositions concerning quadrilaterals. We are justified in assuming that the author tells us all he knows about these figures. The square is defined as a quadrilateral with equal sides and angles, and the rectangle as a quadrilateral with unequal sides and equal angles, but it is not mentioned that these angles are right angles, which we certainly would regard as an important characteristic. There is no doubt that the author of the *Mishnath ha-Middoth* knew the fact, however, for we see it from paragraph IV, 2, where the right triangle is said to be the half of the rectangle and the angle is characterised as an upright one. We see it also from III, 4-5, where the rhombus and the parallelogram are said to have oblique angles, which implies that the former figures (the square and rectangle) have right angles.

On the other hand the *Mishnath ha-Middoth* shows no knowledge of the measurement of the oblique angles. The author did not know that the opposite angles of the rhombus and rhomboid are equal, although he mentions that the sides of the rhombus are equal and that there are in the rhomboid two pairs of equal sides (lengths and breadths). All that the author knows about the angles of the rhombus was that there is one pair of narrow and one pair of broad angles. He does not mention (48) that the two angles at the base of the isosceles triangle, as well as all the angles of the equilateral triangle, are equal, although mention is made of the equality of angles in the square and rectangle. Indeed in the whole book no mention is made of the equality of any two oblique angles. Hence the conclusion is justified that the mensuration of oblique angles, with the possibility of establishing an equality between two such angles, was entirely unknown to the author. That angles are equal, can, in his opinion,

(46) See *Mishnath ha-Middoth*, IV, 2, 4, 9, 10, III, 5, 4.

(47) III, 1-3. AL-KHOWÂRIZMÎ, however, expressly says that they have right angles (p. 55 of the Arabic text).

(48) See the fourth chapter dealing with trilaterals.

be said only of right angles; equal angles in his view, is only a different name for right angles. This is perhaps the reason that he omits to define square and rectangle as having right angles; equal angles, in his judgment, being necessarily the same as right angles (49).

This poor development of the theory of angles is quite natural as a consequence of the fact that the phenomenon and theory of parallel lines was entirely unknown to the author of the *Mishnath ha-Middoth*. There is not even a word relating to parallelism in the whole Hebrew literature of that time. The Hebrew terms *nokheḥî* or *maqbîl* are new words belonging to the Arabic period, beginning at about 900 C. E. The *Mishnath ha-Middoth* has no word for the parallelogram. This is defined either as a quadrilateral with equal sides and unequal angles (the rhombus), or as a quadrilateral with unequal sides and angles, (the rhomboid), having two pairs of equal sides and having oblique angles. The area of the parallelogram is obtained by dividing it into two triangles and computing the area of each triangle for itself as is the case with the trapezoid. (50) The *Mishnath ha-Middoth* does not show any knowledge of the fact that the parallelogram is bisected by the diagonal and that its area is *bh*.

IV. The Theorem of Pythagoras (*c.* 540 B. C.).

13. — *The Hebrew Form of the Pythagorean Theorem.*

It is of great interest to note the way in which the *Mishnath ha-Middoth* gives form and expression to the theorem of Pythagoras. The fourth chapter deals with triangles in the following way: (51) « There are three kinds of trilaterals, to wit: the upright, acute, and obtuse ones. Which is the upright one? When the sum of the squares of its two short sides is equal to

(49) A vague reminiscence of this primitive conception might be found in Euclid's definition of the right angle (*Elements*, I, def. 10): « When a straight line set upon a straight line makes the *adjacent angles equal to one another*, each of the equal angles is right »

(50) See III, 4-5.

(51) The translation is not complete, nor strictly literal. It is rather a free and abbreviated rendering of the content stressing the points relating to the problem in discussion. These points are given literally.

the square of the long side. The area is obtained by the multiplication of one of the short sides in the half of the other one. And the angle standing between the short sides is an upright one... How is the acute trilateral? When the sum of the squares of the two short sides is greater than the square of the long side. Thus you find the angles to be acute... How is the obtuse one? When the square of the long side is greater than the sum of the squares of the short sides... You find thus one of the angles to be obtuse and broad ». This chapter is thus primarily concerned with trilateral figures and with their classification, definition and mensuration. The right, literally « the upright standing », acute and obtuse trilateral are not defined by their right, acute and obtuse angles. The author is apparently more familiar with lines and surfaces, than with angles, and it would be absurd for him to define the known thing by the unknown one. (52) He only incidentally, in a parenthetic, passing remark, mentions that the angles contained by the short sides are respectively right, acute or obtuse. Thus he defines the right angle as standing between the short sides of the upright trilateral, not the upright trilater as having a right angle (53). The real definition of the upright, acute and obtuse trilateral consists in the relation of the sum of the squares of the two short sides to the square of the hypotenuse or long side. In the upright trilateral we have $a^2 + b^2 = c^2$, in the acute one $a^2 + b^2 > c^2$ and in the obtuse one $a^2 + b^2 < c^2$.

In this enlarged form the Pythagorean theorem was already known to HIPPOCRATES OF CHIOS (*c.* 460 B. C.) (54). However, the Hebrew form of the theorem from the square of the hypotenuse differs from the Pythagorean theorem in two regards. (1) In the *Mishnath ha-Middoth* this theorem does not refer to angles at all, but to solid, massive trilaterals, and the term angle does not even occur in the Hebrew proposition. (2) It does not appear as an abstract theorem, but rather as a characteristic, or as a practical rule for finding how to construct the upright, acute

(52) The same is the case with the definitions in I, 2-3. The elements of the quadrilateral are side, diagonal and area. The elements of the trilateral are the side-pair, the base, the altitude, and the area. No mention at all is made of the angles.

(53) Cf. hereafter, § 15-18.

(54) See CANTOR, I, 4th ed., pp. 208-209. Cf. also EUCLID I, prop. 47; II, propp. 12-13. TROPFKE, IV, 2nd ed., p. 146.

and obtuse trilateral. It is the so-called converse of the Pythagorean theorem, stating that an angle is a right angle when $a^2+b^2 = c^2$ but applied to trilateral figures instaed to angles (55).

14. — *The Origin of the Pythagorean Theorem.*

Here again the *Mishnath ha-Middoth* seems to represent the ancient, primitive stage of mathematics. It is now generally assumed that the proposition from the square of the hypotenuse was well known long before the time of PYTHAGORAS. Yet the ancient Oriental races did not know it in its Greek form as an abstract theorem of geometry of angles, but as a practical rule of geometry of lines for construction of perpendicular lines or rectangular edges in their architecture and mensuration. The Pythagorean numbers 3, 4, and 5, or 5, 12 and 13 etc., were known and used by the Hindu ropestretchers to construct rectangular altars, the Chinese availed themselves of these numbers for construction of the *Kun*, (gnomon), and the Egyptians for the erection of their temples or for the making of the right angled instruments of their artisans (56). And in this ancient original form, as a characteristic and practical rule for the construction of upright triangles, it is still preserved in the *Mishnath ha-Middoth*, and in the converse given by EUCLID and HERO.

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(55) Cf. EUCLID I, propp. 47-48; II, propp. 12-13; HEATH, *Euclid*, I, pp. 349, 368, 403-408; HERO, *Opera Omnia*, vol. III, p. 209 and in *al-Nairizi*, ed. CURZE p. 109; CANTOR, I, 4th ed., p. 371; TROPFKE, IV, second ed., p. 149. The Pythagorean theorem in its enlarged form is given by EUCLID, I, prop, 47; II, propp. 12-13; the converse of it is given by HERO, *loc. cit* and by EUCLID I, prop. 48. H. SCHAPIRA, in his edition of the *Mishnath ha-Middoth*, pp. 26-27, note 4, has already noticed this second difference, that the theorem is brought in the form of the converse. SCHAPIRA also referred to the fact that the Arab mathematicians, AL-KHOWÂRIZMÎ, AL-KARKHÎ (c. 1020) and BEḤÂ EDDÎN (c. 1600) bring this theorem also in its converse. The truth, however, is that AL-KHOWÂRIZMÎ also brings the Pythagorean theorem in its usual Greek form with a proof (*Algebra*, Arabic text, pp. 53-54). On p. 57 he brings the version of the *Mishnath ha-Middoth* defining the upright, acute and obtuse trilateral as having $c^2 \gtreqless a^2 + b^2$. Then again he changes his terminology calling them « the one with an upright angle » (p. 57, line 13), « the one with an acute angle » (p. 58, line 7; p. 59, line 10), and « the one having an obtuse angle » (p. 61, line 5).

(56) See CANTOR, I, 4th ed. pp. 104-106, 636-637, 679-680; SMITH, *History*, II, p. 288, HEATH, *Greek Mathematics*, I, pp. 145-47; TROPFKE, IV, pp. 139 seq. There is also an article by O. NEUGEBAUER entitled Zur Geschichte der Pythagoräischen Lehrsatzes in *Göttinger Nachrichten, Math. nat. Kl.*, 1928, p. 45 ff., but I was unable to see it.

From the historical point of view it would, therefore, be more proper to speak of the Pythagorean theorem as of the *converse* of the old Egyptian-Chinese-Hindu rule. Here again (57) we might properly say that the great discovery of PYTHAGORAS lay in making the subject abstract, in converting the old practical rule of the artisans to a fundamental theorem of abstract geometry, in developing the primitive geometry of lines to the science of angle-geometry.

V. THE PERPENDICULAR AND THE GNOMON.

15. — *Terminology of the height.*

In the preceding two chapters the poor development of the knowledge of angles in the *Mishnath ha-Middoth* was shown. This is further demonstrated by the theory of the height.

There are different terms for the height or altitude in the various figures. (1) The solids with an even thickness, like prisms, cylinders and spheres, have « depth » (*'Omeq*) (58) Arabic *'umq*, Greek *βάθος*. (2) The decreasing solids, like pyramid, cone and frustum, have « height, altitude », *qômah* (59) ; (*ὕψος*). (3) In the triangle the height is called *'ammûd*, « pillar, column » (60. (4) The height of the segment is represented by the « arrow », *ḥēṣ* drawn from the mid-point of the arc to the mid-point of the chord (61). AL-KHOWÂRIZMÎ uses *'umq*, « depth », for parallelopipeds, and the Hebrew word *'ammûd* for triangles and decreasing solids (62). It is worth while to note that both the *Mishnath ha-Middoth* and AL-KHOWÂRIZMÎ have no term, nor the idea, of an altitude of the quadrilaterals. Squares and rectangles have length and breadth; the other quadrilaterals are divided into triangles.

16. — *Definition of the height.*

Now it is very instructive and characteristic for the stage of

(57) Cf. end of chapter II.

(58) II, 5, 6; V, 1.

(59) II, 7, 9, 10.

(60) I, 3; *II*, 2; IV, 1-10. The form ômêd in II, 2, is apparently a corruption of *ammûd*.

(61) I, 5; II, 4; V, 5-7. Cf. the term *sagitta*.

(62) H. SCHAPIRA, ed. of *Mishnath ha-Middoth*, p. 21, note 5, justly remarked already that the *Mishnath ha-Middoth* could not possibly use the term *'ammûd* for the height of pyramid and cone, because it employs the same word as name for the frustum.

mathematical knowledge of the author of *Mishnath ha-Middoth*, that not once in all these cases does he remark that the height forms a right angle with the basis (63). He certainly knows it (64), but, apparently, does not deem it proper to define the height by this characteristic. Of the « depth » of the solids it is required « that it be straight and nice » (65) which means that the thickness be equal through the whole height. The altitude of the trilateral is defined as follows : (66) « And the pillar, that is the common thread which runs from between the side-pair down to the base. And it is in the corner ' To the corners of the Tabernacle ' (67) The whole definition is unclear. In speaking of the trilateral, the *Mishnath ha-Middoth* most probably thinks of the isosceles (68); hence the « side-pair » and the « base ». The « common thread » seems to be the diagonal of the parallelogram, whereof the triangle is the half. The isosceles is completed to a rhombus by constructing an equal isosceles at the base, and the height is demonstrated as the thread (diagonal) « common » to both triangles, namely as the diagonal of the rhombus generated by doubling of the isosceles (69). The area of the rhombus is given in the *Mishnath ha-Middoth* (70) as half the product of the diagonals; hence it must know that the diagonals are perpendicular to one another. In the constructed rhombus the base of the isosceles trilateral is the one diagonal, and by drawing of the second diagonal the perpendicular is obtained.

In the same way the height of the segment, the so-called arrow,

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(63) Here again AL-KHOWÂRIZMÎ represents the more advanced stage by expressly saying that the perpendicular forms a right angle; see *Algebra.*, Arabic text, p. 58, line 11; p. 61, lines 1-2.

(64) Cf. IV. 2, where a right angle is said to be contained by the two short sides of the upright trilateral, and the two short sides are called the two « pillars » or « heights ».

(65) II, 6.

(66) I, 3.

(67) *Exodus*, XXVI, 23. The last sentence and the quotation from the scriptures are rather obscure. « In the corner » means perhaps that it comes from the corner, but certainly not that it forms an angle with the base, as SCHAPIRA in his edition, pp. 15, 54, thinks.

(68) The same is the case in Egyptian geometry; see CANTOR, I, 4th ed., p. iii.

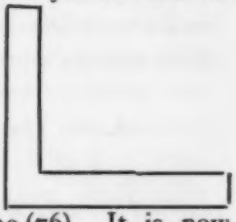
(69) Cf. COLEBROOKE, p. 59, note 2 : « A thread... is the diagonal or diameter of a tetragon... Or in the case of a triangle, it is the diagonal of the parallelogram, whereof the triangle is the half ».

(70) III, 4.

is not defined as forming a right angle with the chord, but as « the straight line drawn from the mid-point of the arc to the mid-point of the chord » (71). Thus the author of the *Mishnath ha-Middoth* gives rather instructions how to construct the height (72), than a definition. EUCLID, however, clearly defines the height of any figure as the perpendicular drawn from the vertex to the base (73), the perpendicular as forming a right angle, and the right angle as one of two adjacent angles being equal to one another (74).

17. — *The definition of* OENOPIDES OF CHIOS (c. 450 B. C.).

A similar phenomenon in Greek geometry might perhaps help us to a better understanding of the *Mishnath ha-Middoth*. In his commentary to EUCLID, *I*, *proposition* 12; « To draw a perpendicular to a given straight line from a point outside it », PROCLUS says (75) : « This problem was first investigated by OENOPIDES (of Chios, *c.* 450 B. C.)... He, however, calls the perpendicular in the « Archaic manner » (a straight line drawn) *gnomon-wise* (*κατὰ γνώμονα*) because the gnomon is also at right angles to the horizon ». The gnomon was an upright style or column erected perpendicularly to a horizontal arm. It was used originally as an instrument of the artisans, a carpenter's square for drawing right angles, and also as an astronomical instrument for the measuring of time by the measuring of the shadow which the column cast on the horizontal arm or plane (76). It is now evident that OENOPIDES, too, did not define the perpendicular as forming a right angle, but as a « gnomon-like » line, as a line



(71) I, 5.

(72) Cf. EUCLID, *Elements*, I, propp, ii, 12; HEATH, I, p. 271.

(73) *Elements*, VI, def. 4.

(74) *Elements*, I, def. 10.

(75) *Proclus on Euclid*, I, p. 283, 7-10; HEATH, *Euclid*, I, pp. 271-272; *Greek Mathematics*, I, p. 175.

(76) See HEATH, *Greek Mathematics*, I, p. 78 seq.; SMITH *History*, II, pp. 601 seq., 670 seq.; CANTOR, I, 4th ed., pp. 161, 190, 536. For further details see the writer's article « On the Origin of the Gnomon », which will perhaps appear in the new issue of the *Bibliotheca Mathematica*.

drawn in the manner of the « upright column » of the gnomon (77). OENOPIDES, too, knew that the perpendicular forms a right angle, but in using the « Archaic manner » he called it by the name of the instrument used for drawing right angles. The reason is evident when we will try to understand the mentality of the primitive mind and his « archaic manner » of expression. The abstract conception of a « right angle » is very plain and familiar to us, but it was not so to the primitive man. He knew very well what an « upright stick », a « pillar », a « column », a « carpenter's square » and an « upright standing man » is, but he did not know of angles and angle-geometry. When he started to observe and to study angles, he defined the right angle as an « upright » angle (78), standing between the upright column and its horizontal basis. But it would seem to him ridiculous and sophisticated to define the column as forming a right angle. The concrete upright stick or carpenter's square is the prior and the abstract notion of a right angle is deducted from it. Man first learned to know the gnomon, the mechanical angle instrument and then the right angle. Hence « right angle » is explained by « gnomon-wise » or '*ammûd* (79), and the height or the upright column cannot be explained by the right angle. On the other hand the definition of EUCLID is characteristic for the mentality of the scholar who defines a concrete thing by an abstract notion.

18. — *The Right Angle as a Unit of Measurement.*

At the time of EUCLID angle-geometry and angle-mensuration reached already a high stage of development. The right angle, fractions and multiples of it, became the standard of angle-measurement and as such a very common notion, and so it is quite natural that it served as characteristic element in the definition of figures and lines. Still EUCLID's conception of the angle was confined to the idea of inclination or difference of direction. The conception of the angle as an amount of rotation was not known in Ancient

(77) Or rather : in the manner of the « carpenter's square »; see « On the Origin of the Gnomon »...

(78) *γωνία ὀρθή*. zawîth nissabâ.

(79) *Ammûd* and *gebû*, « column » and « basis », are in all likelihood, the names for the vertical and horizontal arm of the Hebrew gnomon. So that *'ammûd* corresponds to the Greek *κατὰ γνώμονα*.

Times. Hence antiquity does not recognize angles equal to or greater than two right angles, nor does it know of the zero angle or of the angle $n\pi$. Although the division of the circle into 360 degrees was familiar to the ancient nations, this division referred only to the circumference. The angle-degree and the conception of the circle as an angle of 360 degrees was strange to antiquity (80).

VI. Lateral and Angular Definition of Figures.

19. — *Were the Figures named according to the number of their Sides or of their Angles?*

Cantor (81) says: « Die Zahl der Ecken, in welchen jene Flächen, jene Linien aneinanderstossen, wird ihm (dem Menshen) der Bemerkung wert gewesen sein, wird ihn herausgefordert haben, jenen Gebilden Namen zu geben. » Cantor, apparently, *thinks* of the *Greek* terminology, classifying the figures according to the number of their angles, as *τρίγωφνον*, *τετράγωφνον* and *πολύγωφνον* the triangle, quadrangle and polygon (many-angle »), but he *speaks* of *mankind in general*, as if this Greek terminology were the general usage common to all mankind. An examination of the facts, however, will show that mankind in general, the ancient Egyptians, Hebrews, Arabs, Hindus, Romans and probably also the Babylonians and ancient Greeks, themselves, first noticed only the dimensions of length and breadth, the sides and lines, and named the figures after their number. The observation of the corners and angles, and the classification according to their number seems to be distinctly Greek, a specific invention of Greek science, based upon the introduction of angle-geometry.

20. — *Egyptian, Hebrew and Arabic Usage. Not specified Terminology.*

In the Rhind Mathematical Papyrus we have the word *'ifd* which is generally translated « square » or « rectangular ». « It

(80) See Smith, History, II, p. 277; Tropfke, IV, second ed., pp. 49, 47. Heath, *Euclid*, II, pp. 47-49, 275-76; Cantor, I, 4th ed., pp. 47, 50, 360, 366, 416, 681.

(81) I, 4th ed., p. 15.

is clearly a derivative of *fdw*, the numeral 4, and its original meaning must therefore have been four-sided, perhaps with the tacit addition of rectangular » (82). Every one will agree with PEET that the word *'ifd* = « four-fold » refers only to the four sides and not to the four angles. As we have seen, the Egyptians are primarily concerned with the mensuration of areas and volumes by their sides and not by their angles. The angle can hardly play any part in their mathematics since it is not mentioned at all. Hence it would be improbable to assume that with *'ifd* they meant to say the four-angle. The very fact that they simply say « four-fold » proves that they thought only of one thing, the side, to be taken four times. Would they give much thought to the other characteristic, the angle, which also occurs four-times they certainly would have specified their expression as to four sides or four angles.

The same thing is the case with the Hebrew word *rabu'a*, *merubba'*, commonly used in Bible and Mishnah. It is a derivative of *arba'*, « four », and means literally « four-fold », not specifying sides or angles; but there is no doubt about it that it refers only to the four sides of the figure. It is so much so that we even have the word, *reba'*, meaning « the fourth part », « the side, » of the square (83). In the same way the biblical word *shalish* (I Sam. XVIII, 6), meaning « threefold », is conceived by many commentators to mean, like the Greek *trigonon*, a musical instrument in the shape of a triangle ; cf. GESENIUS, *Hebrew Dictionary*. In the *Mishnath ha-Middoth* the words *merubba' ath* and *meshullesheth* and in Arabic the corresponding forms *murabba'ah* and *muthallathah* are the usual terms for trilaterals and quadrilaterals (84). When the *Mishna* and other *Tannaitic* (85) texts speak of triangular or quadrangular houses, then the Greek words *trigon*, *tetagron* are used (86) not *meshullash*

(82) PEET, p. 85. On the tacit addition of rectangular see hereafter.

(83) See *Ezekiel*, I, 8, 17; X, 11; XLIII, 16, 17.

(84) The Hebrew-Arabic murabba'ah, merubba' like the Egyptian *'ifd*, the Greek *tetragonon* and the Latin *quadratum*, are commonly used to mean the square also, the square quadrilateral being mostly used as the standard measure for all the areas and not differentiated from the quadrilateral with oblique angles.

(85) Hebrew sources contemporary to the Mishnah.

(86) Cf. *Mishnah*, Ne ga'im, XII, 1; *Thosephtha*, ib., VI, 3 and *Nazir*, *I*, 2; *Yer.*, *Nazir*, *I*, 2; *Sifrâ*, Meṣora' VI, 2, (ed. WEISS, p. 73a); *Babli*, *Nazir*, 8 b; *Baba Bathra*, 164 b. See also LEVY's Talmudic dictionary, *I*, pp. 392, 441 b;

or *rabbūʿa*. It is interesting to note that they spoke of a circular. biangular, triangular, quadrangular and pentangular house (87). The biangular house was apparently a house in the shape of a semicircle, (88) and the word = *digōn* = δίγωνον is a new formation not known from Greek sources (89). So the Euclidean series of figures according to the number of sides (90) finds here its parallel in a series of figures according to the number of angles; the circular house being a house with one angle, and the biangular house having the shape of a semicircle.

21. — *The Greek Usage. Specified Terminology.*

The next stage in the development of mathematical thought is represented by Greek terminology. The Greeks were the first to abandon the primitive unclear usage of « three-fold », and « four-fold » figures. They considered not only the sides but also the angles of the figures and were confronted by the problem as to which characteristic is more important, the side or the angle. Hence the indistinct word « threefold, fourfold » could no more be satisfactory to them, and so they created the double terminology, classifying the figures according to the number of the sides and of the angles. They speak of the trilaterals, quadrilaterals and multilaterals, (91) and on the other hand also of the triangular, quadrangular and multiangular figures (92) these latter terms being the usual ones.

22. — *The Problem and its Solution.*

The question now arises as to which terminology is the older one. The general opinion is that the nomenclature according to the number of angles is the older one, and that the lateral nomenclature was introduced by EUCLID. HEIBERG (92) even

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KRAUSS, *Qadmoniyyoth ha Talmud*, *I*, 2, p. 288, and *Lehnwörter*, *II*, pp. 197, 260, 272, 429. The term *trigon* occurs also in *Baraitha di Shemuel ha-Qatan*. VI, end.

(87) Babli, *Nazîr*, 8 b, *Baba Bathra*, 164 b.

(88) See commentary of *R. Sh. b. M.* to *Baba Buthra* 164 b.

(89) Cf. however, δγόναλος « with two knots », or « joints ».

(90) See hereafter, p. 477.

(91) *Tripleuron, tetrapleuron and polypleuron.*

(92) *Trigonon, tetragonon and polygonon.*

(92) *Mathematisches zu Aristoteles*, pp. 15, 31, 32.

goes so far as to doubt the Aristotelian orgin of the *Mechanics*, mainly from the fact that the word *tetrapleuron* occurs there for the quadrangle. HEATH (94), following HEIBERG, states that EUCLID first introduced the lateral terminology, and that the reason for it was that he wanted to put an end to the ambiguity in the use by the older mathematicians of the word *tetragonon*, to mean « square » and any « quadrilateral ». EUCLID therefore created the term *tetrapleuron* for the quadrilateral and retained *tetragon* for the square.

The writer does not agree with this theory. 1) It is not proved that *tetrapleuron* was first introduced by EUCLID. The fact is that it does occur in one passage of the Aristotelian books, the *Mechanics* and the *Problems*, respectively (95). HEIBERG, himself, admits that its introduction by EUCLID is only a conjecture, and CANTOR seems to be very sceptical in regard to this conjecture (96). 2) Anyhow the reason given by HEATH does not account for the introduction of the terms *τρίπλευρον* and *πολύπλευρον* (def. 19). As a rule EUCLID in his *Elements* uses only *τρίγωνον* and *πολύγωνον* (97). Apart from that HEATH, himself, concedes (98) that « though EUCLID enabled ambiguity to be avoided, there seem to be traces of the older vague use of *τετράγωνον* in much later writers (e.g. in' HERO and PROCLUS). »

The writer therefore thinks that EUCLID in using the terms « three-four-and manysided » in *def.* 19 had an entirely different aim before his mind, and this aim was to stress the point of the series of figures increasing in the number of their boundary-lines. The order of the figures spoken of in *definitions* 15-20 of *Book* I is (1) the circle, 2) the semicircle, 3) the trilateral, 4) the quadrilateral and 5) the multilateral. PROCLUS and SIMPLICIUS in their

(94) *Euclid*, I, pp. 187-188; II, p. 239. Cf. also TROPFKE, IV, second ed., p. 92.

(95) HEATH, *Euclid*, I, p. 187.

(96) CANTOR, I, 4th ed., p. 254, note 3, says : « HEIBERG, Seite 31 flg., bezweifelt die Echtheit des Aristotelischen Ursprunges (der *Mechanik*) aus sprachlichen Gründen, namentlich wegen des Vorkommens des Wortes *τετράπλευρον* für Viereck, welches erst EUCLID eingeführt habe. Er gibt aber, Seite 32, selbst zu, dass diese, Seite 15, behauptete Einführung durch EUCLID 'nur eine Vermutung, wenn auch eine sehr wahrscheinliche' sei. »

(97) See I, *Deff.* 20, 21, *Propositions*, 1, 4, 5, 6 etc. for the use of *trigonon*, and VI, 20, XII, 1 seqq, for the use of *polygonon*.

(98) *Ib.*, p. 188.

commentaries already pointed out that, in the order adopted by EUCLID for these definitions of figures, the first figure taken is that bounded by *one* line (circle), then follows that bounded by two lines (semicircle), then the trilateral bounded by three lines etc. (99). This explanation of the commentaries is well founded in the words of EUCLID, I, Deff. 15, 18, 19. EUCLID, himself, expressly mentions and emphasizes the point that the circle is bounded by one, the semicircle by two, the trilateral by three, the quadrilateral by four and the multilateral by more than four lines (100). In fact EUCLID in his *Elements* makes little use of the semicircle. Apparently the only reason for introducing the semicircle and its definion (def. 18) is to have a figure bounded by two lines, and to complete the series of figures bounded by an increasing number of lines, most likely taken from an earlier textbook (101). The terms *tripleuron*, *tetrapleuron* and *polypleuron*, however, were probably not created by EUCLID, as HEIBERG and HEATH believe. They were, in the writer's opinion, rather very old archaic terms. In ancient times, as already pointed out above, people were concerned only with mensuration by means of lines, but they little cared for the angles of the figures, since their value for mensuration was not yet discovered (102). Hence the figures were named and classified according to the number of sides and not of the angles. With the beginning of angle-geometry in Greece in the times of THALES and his school (*c.* 600-500 B. C.) the terms *trigonon*, *tetragonon and polygonon* were invented and obtained so much weight that the older names *tripleuron* etc. were almost entirely discarded and became obsolete (103). As a remnant of an ancient time the term *tetrapleuron*

(99) See HEATH, *Euclid*, I, p. 186.

(100) It is, however, very interesting to note that the Talmudic sources, quoted above § 20, speak of the circular, biangular, triangular, quadrangular and pentangular houses. Thus they seem to think of a series of figures increasing in the number of their angles.

(101) The same reason, namely that the classification was taken from an earlier textbook, is also given by HEATH, (*Euclid*, I, p. 189) for the inclusion of definitions of the oblong, the rhombus and the rhomboid in *def.* 22 dealing with the quadrilaterals, although the oblong, rhombus and rhomboid are not further discussed in the *Elements*.

(102) See above, end of chapter *II*.

(103) The rare terms *tripleuron*, etc. are, like the phrase κατὰ γνώμονα used by OENOPIDES for the perpendicular (see above, chapter V, 17), and the phrase of the *similar angles* at the base of the isosceles triangle used by THALES (see HEATH,

is still preserved in some of the Aristotelian writings mentioned above. EUCLID reintroduced these ancient terms for a special purpose, but he retained only *tetrapleuron* (104). Later on, when MENELAUS wrote on spheric trigonometry (*c.* 100 C. E.) and the need arose for the distinction between two kinds of the triangle, the word *tripleuron* was again revived and introduced by MENELAUS as a term for the spheric triangle in contrast with the plane triangle for which he used *trigonon* (105).

22. — *A curious Fact.*

In conclusion the writer wishes to note a rather curious fact. In the Palestinian Talmud the Greek word *γωνία*, *gōnia*, « angle » is supposed to be used in the meaning of « side », latus (106). The Greek dictionaries cite also the meaning « ein eckiger Pfeiler » « an edged pillar ». In the Talmudic sources, quoted above (107), speaking of the house as being circular, *digon*, *trigon*, *tetragon* or *pentagon*, it certainly would be more fitting to understand these words as meaning having two sides (or pillars), three sides (or pillars) etc. (108). If the meaning of « side », « pillar » for *γωνία* should find more support in Greek literature we might perhaps venture the conjecture that orginally *trigonon* and *tripleuron* etc. had the same meaning of « trilaterals » etc.

23. — *The Roman and Hindu Usage.*

In Roman literature too we find the double terminology characterising the figures according to the number of the sides and

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Greek Mathematics, I, pp. 130-131), rather vestigial remnants of an ancient time. It would be very desirable to have a monography written on such archaic terms in Greek mathematics, which were later crowded out by abstract and technical terms invented in the scientific schools from the times of the Sophist still EUCLID. These archaisms form the connecting link between Greek and ancient Oriental mathematics.

(104) *Book IV*, 20, porism; ed. HEIBERG, II, p. 138.

(105) See CANTOR, I, 4th, ed., p. 413 for the occurrence of the word *tripleuron*.

(106) This is the opinion of LEVY in his Talmudic dictionary, *I*, p. 348. Cf. also KRAUSS, *Lehnwörter II*, pp. 168-169. JASTROW, *I*, p. 256; *Arukh Completum*, *II*, pp. 320-21; HILDESHEIMER, *Beiträge zur Geographie Palestina's*, pp. 73-74 explains ginyâ di-ashqalôn as « die Ausbuchtung », the bay, of Askalon.

(107) See § 20.

(108) The Bible verses, *Leviticus*, *XIV*, 37-39, to which these Talmudic passages refer, speak of the walls of the house and not of the angles.

of the angles : *triangulus*, *trigonum*, *trigonium* and *trilatera*, *quadrilatera*, *multilatera* or *plurilatera*. However, the latter terms, stressing the number of the sides, are preferred by the Roman agrimensores, e. g. by BALBUS (1st century C. E.) Apparently because they are the original ancient Latin terms. (109)

The Hindus also name the figures both according to the number of angles and sides. They have *tryasra*, *tricóna* = « triangle », and *tribhuja* = « trilateral » ; *chaturasra*, *chaturcóna* = « quadrangle», and *chaturbhuja* = « quadrilateral » (110). It seems, however (111), that the classification according to sides is more frequent and usual. The terms *tricóna* and *chaturcóna* seem to show Greek influence, while *tribhuja* commonly used for the oblique trilateral, and *sama-chaturbhuja* the « equilateral quadrilateral », commonly used for the square and rhombus seem to be the native, ancient Hindu terms.

After these lines were written, my esteemed friend, Professor B. DATTA, was kind enough to send in the following information for which the writer wishes to express his best thanks :

« The oldest Hindu terms for rectilinear geometrical figures are found to be compounds of number names, such as *tri* (= 3), *catur* (= 4), *sat* (= 6), etc., with the words *aśra* (*asra* or *asri*) and *srakti*. Such names occur commonly in the Vedic literatures, as also in later works. The word *srakti* means « angle ». But there is difference of opinion about the real import of the word *aśra* or *aśri*. Later lexicographers, such as AMARAKOṢA (c. 350 A. D.) interpret it as meaning « angle ». Still later scholiasts are usually loose in their interpretation. They sometimes put aśra = « angle » and at other times, = « side » or « edge ». ÂRYAḄHATA (499 A. D.) calls a « triangular pyramid » as *ṣaḍ-aśrî* and a cube as *dvādaś-āśrî*. So in these two instances, *aśri* certainly means « edge » or « side ». Similar instances occur in the *Arthaśāstra* (c. 350 B. C.) and in the *Suryaprajnapti* (500 B. C.) in which *aśra* and *kona* (= angle) must be interpreted differently, the former meaning « side ». Hence it will have to be concluded

(109) See TROPFKE, IV, second ed., p. 61, quoting *Schriften der römischen Feldmesser*, *I*, pp. 105-106, and *Pseudo-Boethius*, p. 375, lines 15, 16, 20.

(110) See COLEBROOKE, p. 58, note, and BURGESS, E., Sūrya-Siddhānta, New Haven, 1860, p. 95, last line. The book of BURGESS appeared also in the *Journal of the American Oriental Society*, 1860.

(111) From the further information given by COLEBROOKE, *ib*.

that the ancient Hindus named the geometrical figures according to the number of angles as well as of sides. In any case your inference that the « angle-geometry » is due to the Greeks cannot be supported. For the names with *srakti* (angle) occurs much earlier, long before the birth of Greek geometry. Can you account why the Greeks who learnt Geometry from the Egyptians adopted an altogether different nomenclature? At least their earlier literatures ought to reveal names according to the number of sides. I hope you will look into this side of the problem also ».

VII. Brief Summary and Conclusion.

24. — It may be proper to conclude this discussion with a short recapitulation. At the outset a definition was given of the terms geometry of lines and geometry of angles, angle-geometry and trigonometry. The attempt was then made to demonstrate that these two branches, geometry of lines and geometry of angles, represent two stages in the evolution of geometry. The old Egyptian and Babylonian geometry was characterised as a geometry of lines and the invention of the geometry of angles was credited to the Greeks. Greek tradition was vindicated against the theories of some modern historians of mathematics, and in connection with that instinct and science, the prehistoric phases in mathematics were discussed. Hebrew and Arabic geometry were then investigated and shown to constitute a phase of transition from a geometry of lines to a geometry of angles. From this point of view an inquiry was made into the history of the Pythagorean theorem, and it was shown how the conception of the height and of the right angle developed. Finally the question was discussed as to whether the sides or angles formed the characteristic in the classification of the figures.

It is hoped that a little contribution was made towards the explanation and elucidation of these questions. Yet, the examination of these problems requires a thorough knowledge and familiarity in both ancient philology and history of mathematics, and the writer is fully aware of his shortcomings in both these fields. Should this discussion prove of some use to students of ancient philology and history of mathematics, and be it only by arousing their interest in these problems and by stimulating

them to correct and modify some of the findings of this paper, the writer shall deem himself amply rewarded for his labours. (*)

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* I wish to express my appreciation of the assistance of Professor DAVID EUGENE SMITH in the preparation of my manuscript.

History of determinations of the heights of mountains (1)

There have been in vogue three methods of measuring elevations of mountains above adjacent plains or above the level of the sea: The geodetic method, the barometric method, and the boiling point method. Of these, the geodetic method is the oldest and at the same time the most accurate of recent time. It may be considered under three heads involving, respectively, three more or less distinct processes: Determination of heights, (1) by leveling, (2) by measurement of triangles, (3) by determining the distance a mountain is visible at sea.

THE GEODETIC METHOD.

References to heights of mountains found in Greek authors. Omitting references to extravagant and uncritical statements in ancient writings, relating to heights of mountains, we note that the earliest known scientific measurements of mountain heights were made by DICAEARCHUS, ERATOSTHENES and XENAGORAS. The only available information concerning XENAGORAS is given by PLUTARCH. DICAEARCHUS and ERATOSTHENES described their geodetic determinations in books which are now lost. DICAEARCHUS (about 350—290 B.C.), a philosopher about 30 years younger than ARISTOTLE, was born in Messina, but lived in Greece. He was contemporary with EUCLID who wrote his *Elements* between 330 and 320 B. C. ERATOSTHENES flourished about a century later and was a contemporary of ARCHIMEDES. He is celebrated for his measurement of the earth, and for his determination of the distances of the moon and sun from the earth. He is reported to have estimated the altitude of the highest mountains as 10 stades

(1) This article has been prepared in response to Question 7 in *Isis*, 9, p. 425, 1927.

[1850 meters], but no particular mountains are cited, the height of which he determined. (2)

The principal direct sources of information about measurements made by DICAEARCHUS are PLINY, THEON OF SMYRNA, GEMINUS and STRABO. Speaking of the « earth » PLINY states : (3) It is indeed wonderful that with such extensive ocean and land surface it [the earth] forms a sphere. This view is defended also by DICAEARCHUS, an exceedingly learned man, who on the command of the kings has measured the mountains and given the perpendicular height of the Pelion, which he considers the highest, to be 1250 paces [1905 m.; modern estimate, 1585 m.], but this height is vanishingly small in comparison with the circumference of the earth. To me this view seems untenable, for I know that some Alpine peaks, by gradual ascent, rise to not less than fifty thousand paces. » This last figure, if not an error of some copyist, must represent, not the vertical height, but the slanting approach to a mountain and its summit. The mountains which DICAEARCHUS measured are supposed to be those of Macedonia.

THEON OF SMYRNA says (4) that « the difference in altitude of the highest mountains and the lowest places of the earth amounts, along a vertical, to 10 stadia [1850 m.], according to statements of ERATOSTHENES and DICAEARCHUS, and such considerable distances are ascertained by appliances, with the aid of dioptra for measuring distances. »

STRABO (5) refers to POLYBIUS as authority for the statement that DICAEARCHUS and ERATOSTHENES had treated the subject in a scientific manner, and prepared a treatise with maps which was still extant in the time of CICERO.

GEMINUS (6) when arguing that clouds do not reach the top

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(2) See *Eratosthenica*, ed. BERNHARDY, 1822, frag. 39; HUGO BERGER, *Die geographischen Fragmente des Eratosthenes*, Leipzig, 1880, p. 56, 80, 129, 173.

(3) C. PLINI SECUNDI *Naturalis historiæ libri* XXXVII, Liber II, Chap. 65; see in particular § 162 : DICAEARCHUS, Vir in primis eruditus, regum cura permensus montes, ex quibus altissimum prodidit Pelion MCCL passuum ratione perpendiculi. »

(4) THEON SMYRNAEUS (ed. HILLER, Leipzig, 1878, p. 124, 125.)

(5) *The Geography of Strabo*, transl. by H. C. HAMILTON and W. FALCONER, Vol. I, London, 1854, p. 156 (Book II, Chap. IV, § 1).

(6) GEMINI *Elementa astronomiæ*, ed. C. MANITIUS, Leipzig, 1898, Chap. XVII, pp. 182, 183. There appears to be doubt concerning DICAEARCHUS' estimate of

of high mountains, makes the following statement : « The height of the Cyllene mountains amounts, according to the measurements of DICAEARCHUS, to less than 15 stadia [2775 meters], that of Atabyrius to less than 10 » [1850 meters; modern estimate 1390 meters].

These are all the extant direct references to DICAEARCHUS. As to XENAGORAS, PLUTARCH (7) states : « At this place Olympus is, ten furlongs and ninety-six feet in height [1879 m.; modern estimate, 2930 m.], as it is signified in the inscription made by XENAGORAS, the son of EUMELUS, the man that measured it. The geometricians, indeed, affirm, that there is no mountain in the world more than ten furlongs high, nor sea above that depth; yet it appears that XENAGORAS did not take the height in a careless manner, but regularly, and with proper instruments. »

Without naming the men who made the measurements, some further altitudes of Greek mountains are given by ancient writers. STRABO (8) writes : « That which is called the Acrocorinthus is a lofty mountain, perpendicular, and about three stadia and a-half [647 m.] in height. » According to EURIPIDES, this is « the sacred hill and habitation of Venus. »

STRABO (9) says also : « Arcadia is situated in the middle of Peloponnesus, and contains the greatest portion of the mountainous tract in that country. Its largest mountain is Cyllene. Its perpendicular height, according to some writers, is 20 stadia [3700 m.], according to others, about 15 stadia [2775 m.; modern estimate 2374 m.] » The wide divergence of 15 and 20 stadia would indicate that at least one of these figures is a mere guess. Wide from the truth is also the estimate for Cyllene of 80 feet less than 9 stadia [1641 m.] which STEPHANUS BYZANTINUS (10) (geographer, sixth century A. D.) takes from the writings of the Roman architect APOLLODORUS. Evidently greater uncertainty existed regarding

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the height of Atabyrius; it is given in earlier editions of fragments of his writings, not as less than 10 stadia, but as less than 14 stadia. See O. PESCHEL's *Geschichte der Erdkunde*, München, 1877, p. 63.

(7) PLUTARCH's *Lives*, translated by JOHN LANGHORNE and WILLIAM LANGHORNE, London, 1774, Vol. II, p. 169.

(8) *The Geography of* STRABO, by H. C. HAMILTON and W. FALCONER, London, (Casaub. 377 Book VIII, Chap. VI, § 1) 1856, Vol. II, p. 31.

(9) *Op. cit.*, (Casaub. 387. Book VIII, Chap. VIII, § 1) Vol. II, p. 75.

(10) EUSTATHII *Commentarii ad Homeri Odysseam*, Tome II, Lipsiae, 1826, p. 311. (1951, 15 Rom.)

the height of Cyllene than of any other prominent Greek Mountain. Of interest is the following passage in CLEOMEDES (11) (second century A. D.) : « Those who say that the earth cannot be spherical, because of the depressions occurring in the ocean and the elevations of the mountains, speak without reason. The height of a mountain does not exceed 15 stadia and the depth of the ocean is not more. But 30 stadia have a vanishingly small ratio to 80,000 stadia, (the earth's diameter). It is like dust upon a ball. »

Accuracy of Greek determinations. It is to be noted that the particular mountain altitudes which are explicitly ascribed to DICAEARCHUS and to XENAGORAS are more accurate than those not attributed to any one. DICAEARCHUS estimated Pelion about 20 % too high; Atabyrius less than 33 % too high, Cyllene less than 17 % too high. XENAGORAS estimated Olympus 36 % too low. The anonymous estimates for Cyllene vary from 56 % in excess to 31 % in defect.

We have noted a discrepancy between the statements of THEON OF SMYRNA on the one hand, and GEMINUS, PLINY and CLEOMEDES on the other. THEON OF SMYRNA claims that DICAEARCHUS and ERATOSTHENES set 10 stadia as representing the maximum height of mountains (in Greece). This statement appears to be in conflict with GEMINUS who asserted that DICAEARCHUS estimated Cyllene to be less than 15 stadia. It is in conflict with PLINY who attributed to DICAEARCHUS the height of Pelion as being 1250 paces, which is more than 10 stadia. It is in conflict with CLEOMEDES who sets 15 stadia as the recognized maximum mountain height. The motive for setting an upper limit to the heights of mountains was, as previously indicated, the desire to meet the argument that the great height of mountains made it impossible to entertain the theory that the earth was spherical.

The Theory involved in Greek measurements of heights. The theory of the procedure which DICAEARCHUS, ERATOSTHENES and XENAGORAS used in the determination of the altitudes of mountains is nowhere specifically and fully set forth, but it must have been essentially the same as that used by THALES in measuring the heights of the pyramids and the distances of ships at sea : namely, the comparison of similar triangles, usually right triangles. The

(11) CLEOMEDES, *De Motu circulari corporum coelestium.* German transl. in *Ostwald's Klassiker*, No. 220, 1927, p. 36.

theory of problems in surveying is explained by EUCLID in his *Optics*, chapters 19—22. Some centuries later, this subject was set forth more fully by HERON OF ALEXANDRIA, in his *Dioptra*. A modern surveyor might measure an acute angle and a side of one right triangle and then compute the required side. It is not probable that DICAEARCHUS proceeded in this manner, for there is no evidence that there existed in his day tables which would supply the necessary trigonometric ratios corresponding to the modern sine, cosine or tangent. The earliest table of this sort is the table of chords ascribed to HIPPARCHUS, who flourished about 150 years later. By using two similar triangles, geometers performed their computations without trigonometry, by using only the *lenghts* of sides : they did not find it necessary to measure angles in degrees. The theoretical explanations given by EUCLID and HERON, referred to above, involve similar triangles and the measurement only of lengths.

We have no direct knowledge of the instruments used by DICAEARCHUS, ERATOSTHENES and XENAGORAS in finding the elevations of mountains. THEON OF SMYRNA mentions the dioptra in a passage already quoted, but it is not clear whether he meant to say that the dioptra was used at the time of DICAEARCHUS, or only in his own day. A line of inquiry is supplied by POLYBIUS (about 210-122 B. C.) who says (12) that a strategist in war must utilize the sciences of astronomy and geometry for the purpose of finding distances and the heights of walls which cannot be measured directly in the face of the enemy. POLYBIUS does not explain the process. Recently FRIEDRICH HULTSCH (13) pointed out the obvious fact that the height of walls could be ascertained by performing the following two triangulations explained by HERON : (1) To measure an unapproachable distance, (2) To measure the height of a wall or mountain when its distance from the observer is known. HERON's process of measuring the distance from A to an unapproachable point B is shown by Fig. 1, where the distance A Γ, A Δ, Γ E are measured by rods and the distance A B is computed by similar triangles. As in computing the answer, it is necessary to divide by the difference between Γ E

(12) *Polybii Lycortae.. Historiarum libri qui supersunt, Amstelodami*, 1670, Vol. 1, p. 776 (Liber IX, § 19, 5-9).

(13) *Jahrbücher für Classische Philologie*, Leipzig, 1897, p. 49 ff.

and A Δ, accurate measurements are here called for; a small error in that difference causes a large error in the answer.

The second triangulation is evident from Fig. 2. Sighting the mountain top through the dioptra fixes the points H and K on vertical rods. The water-level attached to the dioptra supplies points for finding K Ξ and H Ξ. By the first triangulation the distance B Π to the center of the mountain is ascertained. Thus the mountain height Π A may be computed. It will be observed that in the determination of the horizontal distance to the invisible center of a mountain, the surveyor would be obliged to point his instrument to the peak of the mountain, and to determine the points Δ and Γ in Fig. 1 by the use of vertical rods such as are shown in Fig. 2.

Instruments used by the Greeks. In addition to a rod or a hodometer for the direct measuring of distances, there are five instruments known to Greek antiquity, any one of which might have been used for measuring the heights of mountains: namely the dioptra Fig. 3, the quadrant Fig. 4, the ancient astrolabe Fig. 5, the ancient cross-staff Fig. 6, and the gnomon Fig. 7. Which of these five is most likely to have been used? We are inclined to eliminate the ancient cross-staff. As far as known it was used only by ARCHIMEDES in certain astronomical determinations. The circular cross-piece was designed to measure the disc of the sun and moon, but was not particularly suitable for sighting the top of a mountain. We eliminate also the ancient astrolabe. It was designed more especially for use in astronomy to measure angles in degrees. We eliminate the quadrant; its degrees are superfluous; its radius was too small for marking the level accurately. As regards the gnomon, it is unsuitable, except for mountains favorably located, so that the shadow of the peak of the mountain could be conveniently marked. It demands a special location for the observer. There is no mountain which is known to have been measured by the Greeks, using the method of shadows. PLINY (14) states that Mt. Athos at the summer solstice casts its shadow upon the market place of Myrina, which was 5000 paces from the island Thasos. That this fact was utilized for ascertaining the height of Athos has been conjectured

(14) PLINY, *Naturalis historiae*, Book IV, Chap. 23, 8.

Fig. 1. From HERON's *Dioptra*, VIII., ed. H. SCHÖNE, Leipzig, 1903, p. 220. This shows how the distance A B is obtained, after A Δ, A Γ and Γ E have been measured.

Fig. 2. From HERON's *Dioptra*, XII., ed. H. SCHÖNE, p. 229. It shows how the height Π A may be obtained, when B Π and the triangle H Ξ K are known.

Fig. 3. HERON's *Dioptra*, III, ed. H. SCHÖNE, p. 193, showing the instrument called « dioptra », the forerunner of the theodolite. It contains no graduation into degrees.

Fig. 4. Quadrant, from PTOLEMY's *Composition Mathématique*, ed. HALMA, Vol. I, Paris, 1927, p. 48. Using the plumb-line, this could be made to serve as a level. Placing the eye at the center and looking at the mountain top, the points H and K demanded in Fig. 2 could be located on the rods.

Fig. 5. Ancient astrolabe (armilles solsticiales), from PTOLEMY's *Composition Mathématique*, ed. HALMA, Vol. I, 1927, p. 64. Using a plumb-line, the inner circle, which turned in the plane of the graduated outer circle, could be used to fix a horizontal direction. Placing the eye near the center of the astrolabe, the points H and K in Fig. 2 could be located.

Fig. 6. A forerunner of the cross-staff, used by ARCHIMEDES for determining the diameter of the sun and moon. If placed on a level platform, and if the position of the movable circular disc be adjusted, so that the eye at the end of the staff would see the top edge of the disc exactly in line with the mountain top, then without the use of surveying rods, data could be obtained corresponding to the triangle K Ξ H in Fig. 2. This drawing is taken from *Archiv. f. Geschichte d. Math., d. Naturw. u. d. Technik*, Vol. 10, 1928, p. 464. The level platform could have been the chorobates in Fig. 9.

Fig. 7. The Gnomon, first used by the Babylonians. Simply a vertical rod, casting a shadow upon a horizontal plane. From the lengths of rod and shadow, and the length of the simultaneous shadow of a mountain, its heigth could be computed. This figure is from *De Quadrante geometrico, by* CORNELIUS DE JUDEIS, Nürnberg, 1594.

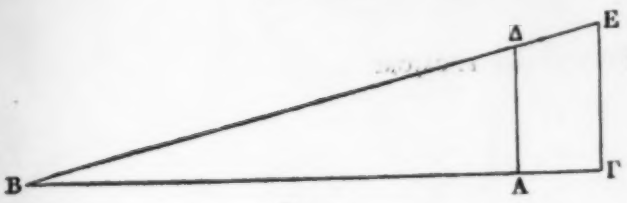

Fig. 1

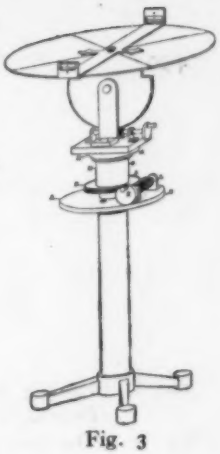

Fig. 3

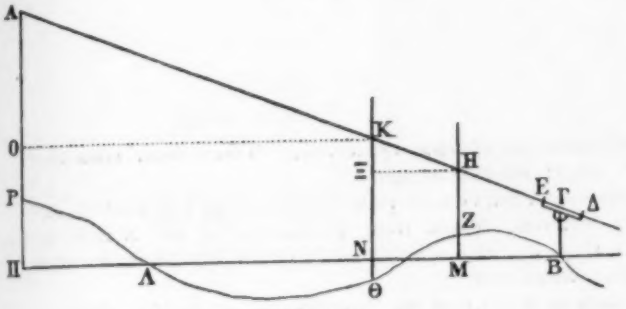

Fig. 2

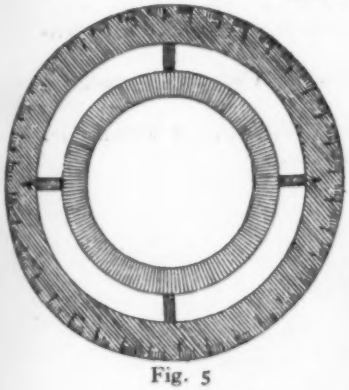

Fig. 5

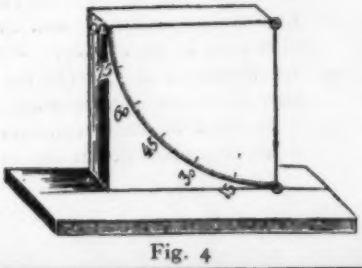

Fig. 4

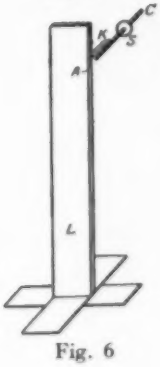

Fig. 6

Fig. 7

F. CAJORI. History of determinations of the heights of mountains.

Fig. 8. Finding differences in altitude by leveling. Taken from HERON's *Dioptra*, VI, ed. H. SCHÖNE, p. 207.

Fig. 9. The chorobates of VITRUVIUS, an early instrument used in leveling, as restored by NEWTON. Taken from *Transactions of the Newcomen Society*, Vol. II, p. 51. It was a rod twenty cubits (9 m.) long, having two legs and a water-level.

Fig. 10. GERBERT's drawing to explain the determination of heights. *Œuvres de Gerbert*, ed. A. OLLERIS, Paris, 1867, Figs. 56, 57.

Fig. 11. Use of the quadrant in determining elevations, as explained by ORONTIUS FINE in his geometry, Paris, 1556.

Fig. 12. An instrument designed by the Academicians at Florence for measuring changes in atmospheric pressure.

Fig. 13. A modified instrument designed by the Academicians at Florence for determining changes in atmospheric pressure.

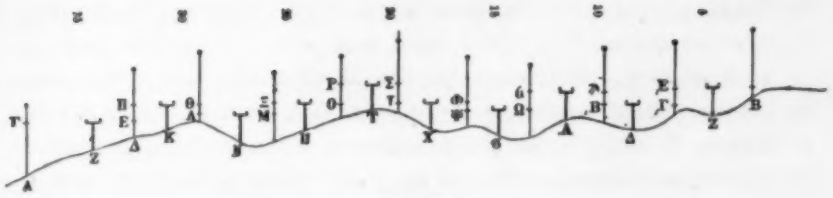

Fig. 8

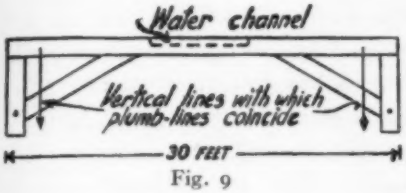

Fig. 9

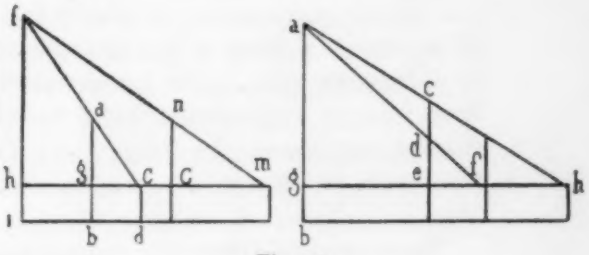

Fig. 10

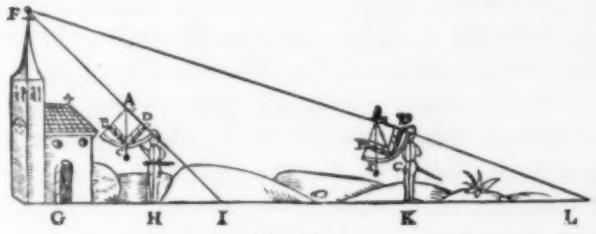

Fig. 11

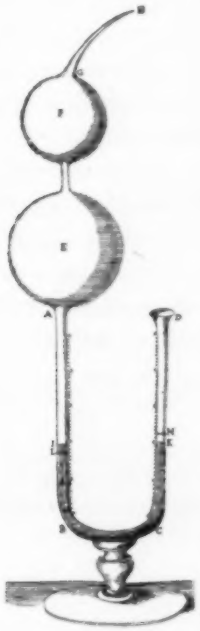

Fig. 12

Fig. 13

F. CAJORI. History of determinations of the heights of mountains.

by VARENIUS (15), but without satisfactory evidence. VARENIUS supplies additional but hypothetical data, and explains the method of computation. Reference to the shadow of Athos is made by more recent writers, for example, MANDEVILLE (16) and KEPLER (17). ROBERT HUES (18), a sixteenth century classical scholar, comments as follows : « One of the most miraculous things which they have discovered of the mountain Athos is, that whereas it is situate in Macedony, it casts a shadow into the market-place of Myrrhina. a towne in the Island Lemnos, from whence Athos is distant 86 miles. But for as much as Athos lies westward from Lemnos, no marvaile that it casts so large a shadow, seeing that we may observe by daily experience, that as well when the Sun riseth as when it sets, the shadows are always extraordinary long. »

The dioptra of HERON, or some similar instrument which may be less complicated, is the only one remaining. Some such type was probably used by DICAEARCHUS and later surveyors, in finding the elevations of mountains. HERON says that his one instrument accomplished everything which several other older instruments did. Probably one of those older instruments was the water-level.

The height of hills could be ascertained by the process of leveling, as shown by Fig. 8, taken from HERON's *Dioptra*. Operations of leveling must have been practised ages before the time of HERON. Says a modern engineer : « There are many examples of large ancient engineering works which required precise leveling, such as the canal between the Nile and the Red Sea, open B. C. 250, after 600 years' construction ; the canal through Mount Athos, six miles long, cut by XERXES, B. C. 480, probably the most famous as well as the most ancient of ship canals. Traces of it are still visible. An interesting example is that of the canal at Corinth, projected by PERIANDER, B. C. 600; 650 years later, in the time of NERO, his engineers came to the conclusion that the canal could not be dug, as the sea was higher on one side of the Isthmus

(15) B. VARENIUS, *Geographia generalis*, edition by I. NEWTON, Cambridge, 1672, p. 62.

(16) *The Travels of Sir John Mandeville*, London, 1900, p. 12.

(17) J. KEPLER, *Opera omnia* (ed. CH. FRISCH), Vol. VIII, 1866, p. 93.

(18) ROBERT HUES, *Tractatus de Globis*, edited by C. R. MARKHAM, London, 1889, p. 8.

than on the other, and consequently would wash away the island of Aegina. » (19)

Leveling is the only operation in surveying which in ancient times had attained a precision which is comparable with the precision in modern leveling. The reason for this lies no doubt in the inexorable demands of nature; water would not run up hill.

From Eratosthenes to Jean Picard (about 150 A. D. to 1672). For about 1800 years after the time of ERATOSTHENES, no noteworthy progress was made in the accuracy of geodetic measurement. To be sure, tables of the natural trigonometric functions and the general development of plane trigonometry made the solution of triangles easy. But practical measurement remained as crude as ever. A slight modification of the procedure described by HERON is found in the writings of GERBERT in the tenth century, who measures a base line directed to the center of the mountain. The general plan is clear from Fig. 10. GERBERT did not actually determine mountain heights by the process which he describes. Nor did ORONTIUS FINE, who was professor in Paris and described this method by the use of a quadrant as shown in Fig. 11. We shall see that this same placing of the base line was used in 1724 by Father FEUILLÉE at the Peak of Teneriffe of the Canary Islands.

It is not surprising that even mathematically trained writers will err in making estimates of mountain heights which they did not base on actual determination of distances and angles. Their imagination, unchecked by geodetic measurement and computation, took flights which would do justice to a JULES VERNE. Thus the Arabic physicist ALHAZEN, famous for his experiments on light, would have the tops of the highest mountains reach to eight Arabic miles [about 14800 meters]. Of CARDAN, the sixteenth century algebraist, ROBERT HUES says : « CARDAN and some other profest Mathematicians are bold to raise them up to 288 miles, but with no small staine of their name have they mixed those trifles with their other writings. » (20) Nor were literary men any wiser. SCALIGER, an opponent of mathematical science, gives credence to the stories that Peak Teneriffe rises to fifteen leagues

(19) R. C. SKYRING WALTERS, B. Sc., Assoc. M. Inst. C. E., « Greek and Roman Engineering Instruments », *Transactions of the Newcomen Society for the Study of the history of Engineering and Technology*, Vol. II, London, 1921-1922, p. 51, 52.

(20) ROBERT HUES, *Tractatus De Globis*, ed. 1889, p. 10.

[about 90,000 m.; modern estimate 3711 m.], while FRANCESCO PATRIZZI, an Italian philosopher and orator, when arguing against the sphericity of the earth, elevates this peak to seventy miles [about 105,000 m.].

Three noteworthy determinations of mountain heights were made about the beginning of the seventeenth century. The cone-shaped Cerro di Potosi in Peru, where in 1546 rich silver deposits were discovered, was found to tower 4872 Spanish feet [1377 m.] above the adjoining plain. (21) According to modern estimates, the city of Potosi is 4146 m., and the mountain Cerro 4830 m., above sea-level. Accordingly, Cerro towers 684 m. above the city, which is about half of the seventeenth century estimate.

In Italy the Jesuit GIUSEPPE BIANCANI (22) (Latinized BLANCANUS), from elevations taken at Parma with dioptric instruments, determined the height of Monte Baldo above lake Garda, to be 804 passus of 5 Bologna feet each [1528 m.] The modern figure is 2095 m.

In England, EDWARD WRIGHT (23) in 1589, by measuring a short base line on a hill near Plymouth sound and also certain angles, showed by computation that this hill was 375 feet above the sea. From this and other data he computed the diameter of the earth, which is about 15 % too small. This was a very creditable performance.

A method of computing the height of mountains visible from the sea came into vogue among many writers, which is theoretically extremely simple, but which practically is encumbered by difficulties of such grave nature that it may lead to extravagant error. It is the determination of height by the distance a mountain is visible at sea or by the distance at sea that a ship can be seen from the top of the mountain, or by the depression of the horizon of the sea below the artificial horizon at the mountain top. This method calls for a most simple computation, the solution of a right triangle, the vertices of which are the top of the mountain, the extreme point of visibility at sea and the center of the earth. In solving this

(21) GIUSEPPE D'ACOSTA, *Historia natural y moral de las Indias*, lib. IV, Cap. 6. Reference taken from O. PESCHEL, *Geschichte der Erdkunde*, München, 1877, p. 426.

(22) BLANCANUS, *Sphaera mundi*. Bonon. 1620, Pars III, p. 95; O. PESCHEL, *op. cit.*, p. 426.

(23) EDWARD WRIGHT, *Certain Errors in Navigation detected and corrected*, 3rd. ed., 1657, p. 90.

triangle, the data most commonly used were the radius of the earth and the distance of visibility. But often the radius of the earth was computed from two other data assumed to be known. Computations of this sort were made by many writers, including MAUROLYCUS (24), KEPLER (25), HUYGENS (26) and VARENIUS (27).

Practically the difficulties of this method were insuperable. Before the seventeenth century there prevailed extreme uncertainty relating to the size of the earth. To be sure, ERATOSTHENES had given a good value for the size of the earth, but there was in early days no way of telling that this value was superior to others. EDWARD WRIGHT (28) pointed out in 1610 that the earth's radius was estimated by different writers all the way from 8000 miles to 3200 miles. A second grave source of error arose from atmospheric refraction. Along the horizon, rays of light deviated largely from straight lines, and no reliable tables of correction existed at that time. Mirages are due to this curving. The bending of the rays may make a mountain look very much higher than it really is. To add to the defects of this method, there was no means of measuring with reasonable accuracy the distance from a ship at sea to the center of the mountain at sea level. Sailors reported the Peak Teneriffe to be visible at a distance of four degrees of the meridian. VARENIUS (29) computes from this that this Peak must be eight Italian miles high [11840 meters] « quae incredibilis fere est. » He then allows for refraction, replacing 4° by 3° and finally by 2 1/2°, and obtains for the height 5 and 4 Italian miles ! The difference between guess data and measured data is well illustrated in the case of SNELL. From hear-say data he (30) computed the Peak of Teneriffe allowing 1° for refraction to be 27,000 feet high (an error in excess of 121 %) and of Aetna 25,416 feet (an error in excess of 149 %), but his estimate of the size of the earth, obtained in 1617 from his own very painstaking measurements, although taken at a time when

(24) F. MAUROLYCUS, *Cosmographia*, Venice, 1543, f. 73. Reference taken from G. LIBRI, *Histoire des sciences mathématiques en Italie*, Vol. III, Paris, 1840, p. 113.

(25) J. KEPLER, *Opera omnia* (ed. CH. FRISCH), Vol. VI, 1866, p. 130.

(26) CHR. HUYGENS, *Œuvres complètes*, Tome XV, La Haye, 1925, p. 533.

(27) VARENIUS, *Geographia* (ed. ISAAC NEWTON), 1672, p. 61.

(28) E. WRIGHT, *Certain Errors in Navigation detected and corrected*, 2d., 1610.

(29) VARENIUS, *Geographia*, 1672, p. 60.

(30) W. SNELL, *Eratosthenes Batavus*, Leiden, 1617, p. 257-263.

the telescope with cross wires was still unavailable, was less than 5 % in error.

W. Snell and J. Picard inaugurate modern methods. The realization dawned upon scientists that the finding of mountain heights and the radius of the earth must be approached much more seriously than had been the case before. In place of hours or days of work there was need of months or years. Measurements of base-lines and of angles must be repeated to afford better values and also to convey an idea of the amount of error in the measurements. Moreover, instruments of greater precision were needed. PICARD was the first to use, in geodetic work, the telescope with cross-wires. The problem of finding mountain heights and the radius of the earth came to be intimately connected. Accurate triangulation over large areas made it necessary to erect signals on the crests of hills and mountains tops which could be seen many miles away. The accurate computation of a meridian line made it necessary to reduce distances to sea level. This could not be done unless the heights of the mountain stations above sea level were known.

SNELL's measurements in Holland (1617) initiated an epoch of laborious effort and new technique: so did that of PICARD, in France, 55 years later. Even then approximately reliable tables for correcting atmospheric refraction were lacking. More accurate surveys were made by DOMINIQUE CASSINI, MAUPERTUIS, and others, for the purpose of determining the shape of the earth. Celebrated are the meridian measurements of BOUGUER, GODIN, LA CONDAMINE, GEORGE JUAN and DE ULLOA in the plain north-east of Quito in Equador, which involved the finding of mountains heights.

The Teneriffe Peak. As already stated, the peak was very conspicuous to navigators. Early in the eighteenth century a party of merchants ascended the mountain and an account of that remarkable trip is described by THOMAS SPRAT in his *History of the Royal Society* of London (1722, p. 200). Its height became a matter of general interest. The first geodetic determination of its height, since the time of the inauguration of improved procedure, was made by the Franciscan Father LOUIS FEUILLÉE in 1724. With a chain of 60 feet, he measured a base line pointing toward the center of the mountain, and 210 toises [409.3 m.]

in length. With a quadrant he measured the elevation of the Peak at each end of the base-line. From these data he computed the height of the Peak above sea level to be 2213 toises [4313 m.]. His determination was published in 1751. (31) A foot note to the article, apparently by Abbé DE LA CAILLE, calls attention to the fact that the method followed is not accurate because of the shortness of the base-line, so that an error of only 20 seconds in measuring the angles would result in an error of 60 toises in the height of the mountain. In 1771 BORDA and PINGRÉ (32) combined two base-lines into one large base, and from its extremities took measurements on Teneriffe; they obtained for it a height above sea level of 1904 toises [3711 m.] which is 309 toises [602.2 m.] less than FEUILLÉE's value. According to HUMBOLDT (33), 1904 toises has a probable error of 6 toises or 1/317th of the height.

Nineteenth Century. This century brought many refinements in the technique of geodetic measurements. The process of leveling, which was brought to remarkable perfection by the Greeks, continued to be used in favorable localities. Thus, in the *Report* of the Superintendent of the U. S. Coast and Geodetic Survey for the year 1883, the height of Mount Diablo in California was determined by leveling. Proceeding one way it was found to be 3661.618 feet high; the opposite way, it was found to be 3661.864 feet. The mean was 3661.741 feet or 1116.09 m.$\pm$.03 m.

An idea of the accuracy of modern triangulation is conveyed by T. C. MENDENHALL who in 1893, as Superintendent of the U. S. Coast and Geodetic Survey, stated that in primary triangulation, angular measurements are made with instruments of such precision, and the observations are repeated so many times that « the average probable error of a direction should not exceed 0".1. » Testing triangulation by comparing the computed length of a line obtained through a long chain of triangles with an actual measurement of the same line, it was found, says MENDENHALL, that « in the triangulation between the Maryland and

(31) *Histoire de l'académie r. d. sciences*, Année 1746, Paris, 1751, Mémoires p. 129.

(32) VERDUN, BORDA et PINGRÉ, *Voyage fait par ordre du Roi*, Paris, 1785, Tome I, p. 117, 378.

(33) A. v. HUMBOLDT, *Voyages aux régions équinox.*, Paris, 1814, Tome I, p. 284.

Georgia base lines, 602 miles apart, the discrepancy was scarcely perceptible, being little over half an inch in a thirty-mile line.»

Elevations of mountains have not attained such extreme precision by triangulation, because no such high degree of accuracy has been attempted, and also because of uncertainty in the proper corrections for atmospheric refraction. The amount of refraction varies constantly, as was shown at two elevations in California, Bodega Head and Ross Mountain. The most reliable result for this difference in height was obtained by the spirit-level, viz., 598.74 ± 0.06 m. Using zenith distances, the computed differences for angles taken at Bodega Head were as follows: At 7 A. M., 600.365 m.; at 11 A. M., 599.119 m.; at 1 P. M., 599.489 m.; at 5 P. M., 600.508 m. The corrections in atmospheric refraction were made in accordance with C. M. BAUERNFEIND's investigations (34) which were preferred on account of their completeness. The results indicate that the amount of refraction continually changes. Moreover, the angular determinations made at Bodega Head taken by themselves were found to give too much difference in height, and the angular determinations at Ross Mountain too little difference in height. The observations at Bodega Head, sighting Ross Mountain, yielded 599.473 m.; the observations at Ross Mountain, sighting Bodega Head, yielded 598.533 m. The average of the two is very close to the truth. Similar results regarding atmospheric refraction were obtained at Ragged Mountain in Maine in 1874. (35)

In recent publications of the U. S. Coast and Geodetic Survey, stations are divided into three classes, with reference to elevations: « first, those fixed by direct connection with sea level, the elevations of which are subject to a probable error of ± 0.04 meter; second, the stations in the main scheme fixed by reciprocal measures of vertical angles and subject to probable errors varying from ± 0.1 to ± 1.2 meters; and third, the intersection stations the elevations of which are fixed by measurement of vertical angles which are not reciprocal, the stations not being occupied, and subject to probable errors which may be as great as ± 3 meters.» (36)

(34) *Astronomische Nachrichten*, 1866, Nos. 1478-1487, and 1587-1590.

(35) *U. S. Coast Survey, Report for* 1876, Washington, 1879, p. 362.

(36) *U. S. Coast and Geodetic Survey*. Special Publication No. 74, Washington, 1921, p. 22.

In other recent reports there is a slight variation in the probable error.

The Barometric Method.

Basic qualitative experiments. The « Torricellian experiment » thought out by Torricelli, but first performed by his pupil Vincenzo Viviani in 1643, after he had made the necessary glass tubing, was repeated in 1644 by Torricelli and Viviani who by that time had prepared a larger supply of glass ware. Torricelli described the experiments in a letter to Angelo Ricci in Rome, who, in turn, wrote to Mersenne through whom the experiments became known to B. Pascal and others. Pascal reasoned that if the mercury column is held up simply by the pressure of the air, then the column ought to be shorter at a high altitude. Whether this idea was altogether original with him, or whether it was first suggested to him in a letter from René Descartes, we shall not stop to discuss. (37) Pascal tried that experiment at a high church steeple in Paris, but, finding the results uncertain, he induced his brother-in-law, Florin Périer, to try it on the Puy de Dôme, a high mountain in Auvergne, near Clermont. The experiment was made on September 19, 1648. During the three preceding days Périer had « rectified » 16 pounds of mercury. He filled two equal glass tubes, each 4 feet long, and hermetically sealed at one end, then inverted them over mercury in a vessel. Both marked 26 inches and 3.5 lines as the height of the mercury column. On the day of the experiment, Périer gave one tube to Father Chastin, to observe at Clermont during the day, while he himself, in company with distinguished ecclesiastical gentlemen and laymen, carried the other tube to the top of the mountain, Puy de Dôme [then believed to be 3000 feet or 973 m. high; modern estimate is 1465 m. above see-level], where it registered a height of only 23 inches and 2 lines — a drop of 3 inches and 1.5 lines. This result, says Périer, « ravished us with admiration and astonishment. » The day brought varying atmospheric conditions. He

(37) This question is discussed minutely by Felix Mathieu in *La Revue de Paris*, Vol. 13, 1906, Part II, p. 565-589, 772-794; Part III, p. 179-206; Vol. 14, 1907, Part II, p. 176-224, 347-378, 835-876.

repeated the experiment five times at different places of the summit, under cover of a small chapel and in the open, when in the wind and when sheltered from it, when the atmosphere was clear and when it was rainy or foggy. He says that in each experiment he first carefully freed the tube of air bubbles. We infer from this that the tube was emptied before the apparatus was transported from one place to another, and then refilled for each trial. Arriving at the foot of the mountain, he found his tube to register 26 inches, 3.5 lines, as before.

PASCAL first wrote an account of the experiment or *Récit de la grande expérience de l'équilibre des liqueurs* (38), in November or December, 1648, in which he suggested that the method could be used for determining whether two localities, even when far apart, had the same or different elevations. The *Récit* was printed, but, for reasons now not definitely known, was withdrawn from circulation. Only very few copies were issued. This action was due, apparently, to PASCAL's determination to confine his activities to matters of religion. The Puy de Dôme experiment did not become generally known among scientific men until 1651 when the celebrated anatomist JEAN PECQUET published at Paris his *Experimenta nova anatomica*, in which he described not only the experiments performed by PÉRIER on the Puy de Dôme, but also some experiments by AUZOUT on the Torricellian vacuum which has, however, nothing to do with the effects of high altitude upon the length of the barometric column. (39) PECQUET's book was widely read; it was from this source that SINCLAIR in Scotland, and the Academicians in Florence learned of the Puy de Dôme effect.

Experiments in Florence. The members of the famous Accademia

(38) Printed in *Œuvres de Blaise Pascal* (Ed. L. BRUNSCHVICG and P. BOUTROUX), Vol. II, Paris, 1908, p. 365-373. Later (probably in 1654) PASCAL wrote his well known *Traitez de l'équilibre des liqueurs et de la pesanteur de la masse de l'air*, which was first printed in 1663, after his death. It is reproduced in the *Œuvres*, Vol. III, 1908, p. 143 ff. A facsimile of the *Récit* was brought out in 1893 by G. HELLMANN as No. 2 of his *Neudrucke von Schriften und Karten über Meteorologie und Erdmagnetismus*.

(39) Of experiments on air pressure described by PECQUET, a part (but not the Puy de Dôme experiment) is reprinted in the *Œuvres de Blaise Pascal*, Vol. III, Paris, 1908, p. 238. An account of PECQUET on air pressure is given by F. MATHIEU in *La Revue de Paris*, Vol. 13, Part II, 1906, p. 781, and Vol. 14, Part II, 1907, p. 203.

del Cimento in Florence were led to determine differences in altitude on a new principle, though still using mercury, namely the expansion of the air under diminished pressure, the temperature being invariable. They designed an instrument shown in Fig. 12 (40). At the foot of a steeple in Florence, 142 yards (braccia) in height, they awaited the moment when the temperature was the same as at the top of the tower. Then they poured mercury into the lower tubing, sealed the fine terminus of the glass tube, and carried the apparatus to the top of the tower. The diminished air pressure caused the air in the bulbs to expand so that the two mercury columns which before had been equally high, now showed a difference in height. From this, by BOYLE's law, the difference in air pressure could be ascertained. This apparatus was frail and hardly portable, though some tests were made with it on neighboring hills — « sopra diverse colline di quelle, che la Città coronano. » A modification of this design is shown in Fig. 13, where the tube at D is sealed after the mercury is introduced. When the external air pressure decreases or increases, the mercury in the tube rises or falls. A serious defect of this apparatus was that the amount of the expansion of the air in the receptacle was greatly affected by even slight changes in temperature. This method of determining altitudes never passed beyond the experimental stage. The academicians doubted the possibility of satisfactory altitude determinations by the barometer, for the reason that they had observed fluctuations of barometric readings at one and the same place.

Experiments in Scotland. GEORGE SINCLAIR, at one time professor of philosophy at the University of Glasgow, took observations in the years 1661-1666. (41) From reading PECQUET's book he was familiar with the experiments of PASCAL and PÉRIER. He selected four suitable elevations in southern Scotland, Tinto Hill south east of the town of Lanark, a cliff north of the town of Moffat in the Annan basin, Arthur's Seat east of Edinburgh, and the Glasgow cathedral. He also made tests in mines. Some of the experiments were made in the presence of distinguished persons as witnesses.

(40) *Saggi di naturali esperienze fatte nell'accademia del cimento.* Seconda edizione, Firenze, 1691, p. 62, 64, 66-72.

(41) *Georgii Sinclari Ars nova et magna gravitatis et levitatis. Sive Dialogorum philosophicorum Libri sex.* Roterodami, 1669, p. 125-149.

SINCLAIR selected Tinto Hill because it could be seen from a distance, even from Glasgow. The ascent was made October 12, 1661. « At the summit I filled the baroscopic tube with mercury, observing the greatest care and diligence, foreign things being driven out by means of an iron wire, air bubbles in particular, which lie hid in the mercury. Then, the tube being inverted in the usual manner and the orifice immersed in a bath of mercury, the mercury in the tube did not descend to 29 inches, as was commonly expected, but nearly to 27, after it had come to rest... A long strip of paper was attached to the tube and graduated into divisions and subdivisions, for the purpose of measuring. » SINCLAIR obtained the height of Tinto Hill by measuring at Glasgow its angle of elevation by means of a quadrant, and taking the usual estimate for its distance from Glasgow. He obtained for its height 500 paces or 2500 feet. The modern figure is 2335 feet or 711.7 m.

The vertical cliff north of Moffat indicated a drop of the mercury of 1/4 of an inch. The height of the cliff was not accurately known, but was said to be 50 paces.

At the Glasgow cathedral the mercury tube and reservoir were attached to a rope and raised and lowered repeatedly through a vertical distance of 186 feet; the difference in height was found to be 5/32 of an inch.

At Arthur's Seat near Edinburgh, the column fell from 29 inches to 28 1/4 inches, but SINCLAIR gives no estimate of the height of the hill. Modern determinations are 822 feet above the sea.

BOYLE established the law of gases known by his name, in 1662. SINCLAIR was not familiar with BOYLE's results and proceeded to frame a rule for the variation of the length of the barometric column for different elevations of observation, which was altogether false. He assumed that, if ascending from sea level to a certain height resulted in a drop of the mercury of, say, two inches, then double that height would yield a drop of exactly four inches. SINCLAIR interested himself not only in finding a rule for the barometric determination of mountain heights, but even more in the determination of the actual height of the atmosphere. Taking his Tinto Hill data, he solved the proportion 2 inches is to 500 paces as 29 inches is to x paces. This gave

x = 7250 paces or 36250 feet for the height of the atmosphere. He had more confidence (« plùs fido ») in his cathedral data than in the data for the cliff near Moffat, because he had carefully measured the altitude at the cathedral. Taking his data obtained at the Glasgow cathedral, he obtained the proportion : 5/32 inches are to 186 feet, as 29 inches are to x feet. Here he gets approximately x = 34336 feet, a result for the height of the atmosphere somewhat smaller than his first.

In Germany, OTTO VON GUERICKE (42) proceeded to repeat the Torricellian experiment on the Brocksberg, the highest point in the Harz mountains, southwest of Magdeburg, but he met with an accident. He says : « At the foot of the mountain everything went well, but when I gave the glass tube, which was packed in a tin box, to a servant to carry, he broke it in a fall and thereby the experiment miscarried. »

Early attempts to establish a correlation between barometric height and mountain height. The apparent theoretic simplicity of the barometric method vanished on closer examination. The simultaneous accurate measurements were difficult to make. When one of the measurements was easy, the other was hard. For a steeple, the difference in the mercury column was too small for accuracy. The exact height of any high mountain remained unknown before about the middle of the eighteenth century. But these were not the only obstacles. Indeed, a perfect correlation does not exist, for the reason that there are slight fluctuations in the height of the mercury column at one and the same locality due to changing weather conditions. Nor is the difference in the simultaneous barometric readings of the two places always the same. Technical matters had to be considered in the construction of barometers, to avoid capillary action, to remove air bubbles in the mercury and to attain more accurate methods of measuring the lenght of the mercury column, as well as to secure portability of the instruments. It took a century to develop instruments and to determine accurately the constants which enter into the determination of the altitudes by the barometer. Even then the method did not reach the accuracy which is possible by the modern refined geodetic methods, but it enjoys the advantage

(42) O. GUERICKE, *Experimenta nova*, Amsterdam, 1672, Lib. III, Cap. 30. p. 114. See *Ostwald's Klassiker*, No. 59.

over the latter of being more expeditious. Most of the mountain heights given in geographic tables were determined by the barometric method. In 1807 HUMBOLDT knew of only 122 measured tops. In 1829 GEHLER gave about 4600 heights, most of which were determined barometrically. (43)

The earliest explanation of a process by which a mountain altitude may be computed from the drop of the barometric reading below that at sea level, was given by the French physicist EDME MARIOTTE. (44) He did not develop a formula, but explained roughly the procedure, on the assumption (1) of « MARIOTTE's » (« BOYLE's ») law of gases and (2) the distance above sea level which causes a drop of, say, one line (one-twelfth of an inch) in the barometric reading. From his experiments at the Paris observatory, he concluded that a rise of 84 feet caused a drop of 1/9 of an inch, or 4/3 of a line. This amounts to about 63 Paris feet for 1 line. Being told that at Orleans a rise of 300 feet caused a drop in the barometric reading of 5 lines, which amounts to about 60 feet per line, he took at first, « pour la facilité du calcul », 60 feet per line, but later 63 feet per line. We see here that no great care was exercised to determine accurately the observational constant entering his calculation. He took 63 or 60 feet, whichever best suited his fancy. As a matter of fact, both values were much too small. He applied two checks to his procedure, one being the data obtained by PÉRIER at the Puy de Dôme whose height, as we stated was not known accurately, the other being D. CASSINI's data for a mountain in Provence, 1070 feet high, the mercury dropping 16 1/3 lines. As an explanation of MARIOTTE's method we repeat this last calculation. He computed how far one has to rise at each step to secure a barometric drop of 1 line. The atmospheric pressure at sea level is equal to that of 28 inches or 336 lines of mercury. At an altitude where the pressure is only half, or 168 lines, the altitude of the air column is doubled, that is twice 63 or 126 feet. In the interval between 336 and 168 lines the increase per line is nearly 63/168. Thus, for 16 1/3 lines the total increase would be $63/168\,(1 + 2 + 3 + \ldots$

(43) J. S. T. GEHLER, *Physikalisches Wörterbuch*, Vol. 5, Leipzig, 1829, pp. 339-397.

(44) E. MARIOTTE, *Essai sur la nature de l'air*, 1676; *Œuvres*, nouvelle édition, La Haye, Tome I, 1740, p. 174, 175.

+ 16) = 51. Adding to this the fundamental 63 feet per step, or 63 × 16 1/3 = 1029, yields 1029 + 51 or 1080 feet, as the computed height of the mountain; this is only 10 feet in excess of the measured 1070 feet.

A more finished analysis was published ten years later by EDMUND HALLEY. (45) He showed the great advantage of the use of logarithms, and deduced a formula which yielded the height H in English feet, viz.,

$$H = \frac{900\ (\log\ 30 - \log\ h)}{0.0144765}$$

where 30 inches is the height of the mercury column at sea level, and h inches is its height at the place of observation. HALLEY also took the experimental data in round numbers, so that the constants had to be redetermined later. His formula indicates that a drop in the barometric reading from 30 to 29 inches corresponds to a difference in altitude of 915 English feet, which is about 26 feet too much. In deriving his formula he assumed that mercury is 13 1/2 times heavier than an equal bulk of water and that, water is 800 times heavier than air at sea-level, so that mercury is 10800 times heavier than air. The modern figures for sea-level are more nearly 10500. A cylinder of mercury one inch high weighs therefore, according to HALLEY, as much as a cylinder of air of equal base at sea-level, and 10800 inches or 900 feet high. By BOYLE's law, $pv = 30 \times 900$. Using modern symbols, the cylinder of air reaching from sea-level to the place where the barometric reading is h, is

$$\int v\,dp = \int 30 \times 900 \frac{dp}{p} = 30 \times 900 \log p \Big]_h^{30} = 30 \times 900 \times (\log 30 - \log h).$$

Changing from natural to common logarithms, by dividing by the modulus .434295, and simplifying, HALLEY's expression is obtained.

HALLEY's formula, involving logarithms, has the basic form which was eventually adopted, but for many years it received little attention. JACQUES CASSINI, (46) DANIEL BERNOULLI, (47)

(45) E. HALLEY, *Philosophical Transactions*, London, 1686, p. 104-116; Abridged Transactions, Vol. II, 1705, p. 14.

(46) J. CASSINI in *Mém. de l'Académie r. d. Sciences*, Paris, année 1705 and année 1733.

(47) DANIEL BERNOULLI, *Hydrodynamica*, sect. X.

JOHANN JAKOB SCHEUCHZER, (48) PETER HORREBOW (49) and others set up different rules, none of which proved altogether successful. HALLEY's rule, that altitudes increase as the differences of the logarithms of the atmospheric pressures, was not generally accepted. Thus DANIEL BERNOULLI rejected it as contrary to the observations available to him.

Earliest barometric height measurements. It is noteworthy that during the seventeenth century the barometer was not actually used in the determination of the height of mountains. Observation was confined to the comparison of the height of the barometric column with geodetically determined mountain heights. The first observer to compute previously unknown heights from barometric readings was the Swiss JOHANN JAKOB SCHEUCHZER, in the years 1705-1707. His son, J. K. SCHEUCHZER, in 1727 made the following statement : (50) « My Father, Dr. J. J. SCHEUCHZER, in his Journies over the Mountains of Swisserland, as they were more particularly calculated for the Improvement of Natural Philosophy in it's several Branches, neglected no Opportunity, along with his other Observations, to make such Experiments with the Barometer, as might serve to illustrate the Qualities of the Air, to settle the respective Heights of Places, and particularly to shew, how much our Mountains rise, as well above the Level of the Sea, as above other neighboring Mountains in France, Italy, Spain, etc. Many of these Observations are scattered up and down in his Writings, particularly his *Itinera Alpina*, and the several parts of his *Natural History of Swisserland*, which last work was published in High German. » During these alpine travels, barometric readings were taken also at Zurich. In his early computations. J. J. SCHEUCHZER took 1 line (i.e. 1/12 of an inch) to correspond to 80 feet of elevation; in other words, he took the height of a mountain to be 80 × 12 × 12 or 11520 times the difference of the barometric readings. (51)

It will be observed that this rule is theoretically incorrect.

(48) J. J. SCHEUCHZER, *Bergreise*, Theil II, Zürich, 1746.

(49) P. HORREBOW, *Elementa philosophiae naturalis*, Chap. VIII.

(50) J. K. SCHEUCHZER, *Philosophical Transactions*. Abridged, Vol. VI, Part II, London, 1734, p. 33.

(51) J. J. SCHEUCHZER, *Itinera alpina*, Londini, 1708, *Iter sec.* p. 7. We have not seen this work and we take this reference from O. PESCHEL's *Geschichte der Erdkunde*, München, 1877, p. 690.

Practically the rule yields values that are too high for moderate distances above sea-level. But a few years later a new rule was deduced from new data obtained by J. J. SCHEUCHZER, at the watering place, Pfäffers, where a vertical cliff was measured to be 714 Paris feet high, « as appeared by letting a Line drop down perpendicularly from a Tree at Top, full to the Bottom. » The barometric difference was found « by repeated experiments » to be 10 lines. This determination, says the son, was « the most considerable that ever was made, and which enabled him [J. J. SCHEUCHZER] more particularly to examine the two Tables made by CASSINI THE YOUNGER, according to the Rules of M. MARIOTTE, and the Observations made by him [CASSINI] and others, when the Meridian Line was perfected in 1703. » The height of the cliff corresponding to the difference of 10 lines was found by MARIOTTE's rule to be 696 feet, by JACQUES CASSINI's rule 921 feet, the true height being 714 feet. JOHANN SCHEUCHZER, a brother of JOHANN JAKOB, undertook to calculate a new table from the data obtained at Pfäffers and from the theoretical principles used by HALLEY. If the barometric heights at sea-level and at another locality (expressed in thirds of a line) are designated, respectively, by H and h, then the SCHEUCHZER new rule (52) may be stated in form of a proportion thus :

$$.0142717 : 714 = \log H - \log h : x$$

where x is the required height in Paris feet. JOHANN SCHEUCHZER calculated by this rule that Piz Stella, in the Canton of Grisons, was 9585 Paris feet over the sea. By MARIOTTE's rule it would be 9441 feet, by JACQUES CASSINI's 12,196 feet. (53)

Peak Teneriffe. This conspicuous mountain of the Canary islands, rising from the ocean to a great height, made, as we have seen, a wonderful appeal to the imagination. Is its height 70 miles, as claimed by the philosopher PATRIZZI, or only 7 miles, as guessed by the more restrained, yet exuberant imagination of ROBERT BOYLE? What are the prosaic facts? In 1667 BOYLE wrote : (54) « Perhaps I have told your Lordship already by word of mouth, that I have been solicitously endeavoring to get the

(52) *Philosophical Transactions*. Abridged, Vol. VI, Part II, p. 35.

(53) *Op. cit.*, p. 42.

(54) *Robert Boyle's Works*, Vol. III, 1772. A Continuation of New Experiments Physico-Mechanical, touching the Spring and Weight of the Air, p. 225-228, Experiment XXIII.

Torricellian experiment tried upon the pic of Teneriff, but hitherto I have had no account of the success of my endeavors.» The experiment was first performed more than half a century later. It was in 1724 that Father LOUIS FEUILLÉE determined its height trigonometrically to be 13278 French feet. He also ascended the mountain with a party, taking barometric observations at several places during the ascent. At the top the barometric reading was 17 inches and 5 lines, indicating a drop from the mark at sea-level of 10 inches and 7 lines. No barometric estimate of the Peak's height was published by FEUILLÉE. If we compare the height by the rule of MARIOTTE, taking 63 feet to correspond to a barometric line at sea-level, we obtain 10,424 Paris feet — the trigonometric value of BORDA and PINGRÉ being 11,424 Paris feet. Stern reality forced BOYLE's imaginative 7 miles down to a paltry 2 miles.

Discordant results. In the first half of the eighteenth century, many discordant results were obtained in barometric heights. The French were engaged in meridian measurements, and in the region of the Pyrénées determined mountain heights both geodetically and barometrically. Geodetic measurements, involving checks by the comparison of the measured and the computed values of base-lines, were beginning to indicate such a high degree of accuracy before the middle of the eighteenth century, that the very delicate empirical determination of the flattening of the earth at the poles was triumphantly demonstrated. Careful geodetic measurements of heights were therefore available after 1740, as standards for testing the accuracy of barometric determinations. DE LUC (55) instituted a comparison of results obtained by the different early formulas for a drop of the barometric reading of 5 inches below the height of 28 inches at sea-level. The computed altitudes expressed in Paris feet were according to MARIOTTE, 4170 feet 9 inches; HALLEY, 4998 feet 8 inches; MARALDI, 5430; J. SCHEUCHZER, 4274 feet; JACQUES CASSINI, 4554 feet; DANIEL BERNOULLI, 4782 feet; HORREBOW, 4954 feet 3 inches; BOUGUER, 4954 feet 3 inches. The highest of these values, differed from the lowest by 1260 feet. The correct value is about 4980 Paris feet. The formulas were based partly on the number of

(55) J. A. DE LUC, *Recherches sur les modifications de l'atmosphère*, n. ed., Vol. 1. Paris, 1784, p. 285.

feet of altitude corresponding to a drop of 1 line in barometric readings; this is exceedingly difficult to measure with accuracy. That altitude varied with different early observers from 60 to 80 feet. The true value at sea-level is about 75 Paris feet, slight variations being due to changes of temperature, geographic latitude, aqueous vapor, and other weather conditions.

To secure another glimpse of the discordant results obtained in barometric measurements in the early part of the eighteenth century, we quote data on three mountains in the Pyrénées region of France given by JACQUES CASSINI in 1733 :

	Trigonometric Survey	MARIOTTE's Barometric Rule	MARALDI's Barometric Rule	More recent results
Mont de St. Barthelemy	1190 toise	1012 toise	1427 toise	1192 toise
Mont du Mousset	1289 toise	1035 toise	1467 toise	1236 toise
Canigou	1453 toise	1183 toise	1728 toise	1440 toise

Mont Blanc. DE LUC states that Mont Blanc had been measured trigonometrically by FATIO DE DUILLIER to be 2000 toises (less than 4000 meters) above Lake Geneva, (56) but that, for accurate work, the base was too short and too far removed from the mountain. DE LUC himself, about 1765, determined the height of Mont Blanc in sections, the lower sections being computed barometrically and the uppermost section trigonometrically, from data which he recognized to be of doubtful accuracy. He found the height of Mont Blanc over the sea-level to be 2391 toises which is 4660 meters, the modern estimate being 4810 meters. It was in 1786 that a mountain guide discovered a path to the top of Mont Blanc. The following year the physicist, H. B. SAUSSURE (57) of Geneva climbed to the top and there found the barometric reading 16 inches and .22 lines, the temperature of the mercury being 1.2°R., that of the air — 2.3° R. The simultaneous barometric reading at the astronomical observatory in Geneva was 27 inches, 3.12 lines. By DE LUC's formula with temperature

(56) « Remarque sur l'histoire naturelle des environs du Lac de Genève, » à la fin du II^e^ Vol. de l'histoire de Genève par M. SPON.

(57) H. B. SAUSSURE, *Voyages dans les Alpes*, Tome VII, p. 304. Reference taken from O. PESCHEL, *Geschichte der Erdkunde*, 1877, p. 696. Applying formulas developed later, that of LAPLACE with RAMOND's constant, yielded an altitude of Mont Blanc 56 feet in excess, that of GAUSS yielded 38 feet in excess.

correction, the height of Mont Blanc above Lake Geneva was 13,333 Paris feet; this is 251 feet short of the true value.

Boiling the mercury. Corrections for capillary action and temperature. Differences in the readings of barometers, observed at the same time and place, pointed to the need of greater care in construction. The French physicist DU FAY in 1723 made the suggestion that the mercury in the barometric tube be boiled, in order to expel air bubbles and other impurities. CASSINI DE THURY and L. G. MONNIER found that boiling helped, but Abbé DE LA CAILLE found that boiled and unboiled thermometers which he observed agreed within 1/4 of a line. Hence, for some time, DU FAY's suggestion was not widely followed. Nor were the advantages resulting from boiling at first fully understood. Only later was it recognized, that bubbles and aqueous vapor in the mercury may escape into the Torricellian vacuum and by their elastic force depress the mercury column and distort the barometric readings.

It was found also that insufficient attention had been given to capillary action which causes greater depression of the mercury in a narrow glass tube. DE PLANTADE (58) was one of the first to give this matter serious consideration; he suggested that in all observations the diameter of the glass tube should be recorded.

In the latter part of the eighteenth century there was a small army of scientific workers bending their efforts towards the improvement of the barometer. Outstanding achievements in the experimental and observational side of this work are those of J. A. DE LUC of Geneva in Switzerland. He initiated careful temperature corrections for boiled barometers, and determined the coefficient of expansion of mercury. For unboiled barometers the expansion due to heat was found to be quite irregular. The astronomer LAPLACE (59) endeavored to give due consideration to all reliable experimental data, especially those gathered in the numerous observations in the region of the Pyrénées in France, and taken by L. RAMOND. LAPLACE developed a formula for the barometric determination of altitudes which made allowance also for variation of gravity with the altitude and with the latitude.

(58) *Magasin Français* pour Décembre, 1750; J. A. DE LUC, *Recherches sur les modifications de l'atmosphère*, n. éd., Vol. I, Paris, 1784, p. 94.

(59) LAPLACE, *Mécanique Céleste*, tome IV, livre 10.

Additional improvements were made later. To expedite computation, K. F. GAUSS computed tables giving corrections for the temperature of the air at both stations, and also for the diminished gravity in high altitudes. F. W. BESSEL in 1838 introduced corrections for the humidity of the air. (60) In an altitude of 879.63 toises, computed for a relative humidity of 50 %, BESSEL added 3.24 toises for the case of saturation, and deducted the same amount for the case of perfectly dry air. Since the time of MARIOTTE, many different formulas have been deduced for computing barometric heights. In 1870 RÜHLMANN (61) collected twenty three of them as representing the most important.

Example of early nineteenth century accuracy. An idea of the accuracy and reliability of the barometer as used in 1818, is afforded by the record of THOMAS GREATOREX (62) in measuring Skiddaw in the north of England. The height of Skiddaw above Derwent lake was, by leveling, 936.097 yards; the barometric height was, by MASKELYNE's formula, 936.1685 yards; by HUTTON's formula 935.285 yards. Tests were made 150 yards lower down which resulted as follows: By leveling 786 yards, by MASKELYNE's barometric formula 782.3 yards, by HUTTON's formula 781.4 yards. At still lower points the discrepancy was even greater. GREATOREX remarked: « From the near agreement of the measured and barometric heights on the summit of Skiddaw, I had formed sanguine hopes that the barometer would prove a most exact determinator of altitudes,... but the subsequent observations lead me to fear that the state of the atmosphere has an effect which we cannot yet account for, and to which we cannot apply a correction. »

Hourly and annual barometric fluctuations. L. RAMOND noticed about 1810 that barometrically determined heights varied with the time of day when the measures were taken. His experimental data exhibit also an annual variation. Among those who later occupied themselves with this subject are EMILE PLANTAMOUR, C. M. BAUERNFEIND, RICHARD RÜHLMANN and Major WILLIAMSON of the United States army. GEORGE DAVIDSON of the U. S. Coast Survey, in 1871, gave the following summary: (63) « Among the

(60) *Astronomische Nachrichten*, Vol. 15, No. 357, 1838, p. 360.

(61) R RÜHLMANN, *Die barometrischen Höhenmessungen*, Leipzig, 1870, p. 21-32.

(62) *Philosophical Transactions*, Vol. 108, for the year 1815, London, p. 398-402.

(63) *U. S. Coast Survey, Report for* 1871, Washington, 1874, p. 165.

conclusions reached are the following: Differences of heights, barometrically determined, appear to attain their maximum value shortly before the time of greatest heat of the day; they decrease rapidly during the afternoon, and slowly during the night, reaching their minimum about one or two hours before sunrise... Resulting heights, determined from daily or monthly means, also show an annual period; they are found too small in winter and too great in summer... Heights determined from annual means generally give results differing little from the truth.» DAVIDSON gave a table showing the barometric differences of height between Bodega Head and Ross mountain, in California, for different hours of the day. By his operation of leveling, the difference was 598.72 m. By the barometric method, the difference was at 7 A. M. 598.80, at 1 P. M. 610. 34 m., at 5 P. M. 604.32 m. These hourly variations were supposed to be due to a variable difference in the observed mean temperature at the two stations and the actual average temperature of the intervening stratum of air.

CHARLES A. SCHOTT, of the U. S. Coast and Geodetic Survey, expressed himself in 1876 as follows: «It is evident that further observations are desirable, and that barometric hypsometry cannot be made the basis of exact determinations of heights.» (64)

THERMOMETRIC METHOD

In 1724 G. D. FAHRENHEIT (65) observed the rise of the boiling temperature of water with the increase of the atmospheric pressure. He suggested the determination of the weight of the atmosphere by means of the thermometer alone. A few years later L. G. MONNIER and JACQUES CASSINI showed that this change in the boiling temperature is very considerable (66); it is 7.18 Reaumur degrees for the height of Canigou; this drop is equivalent to 16.15° Fahrenheit. But it was the physicist of Geneva, J. A. DE LUC, who in 1762, when on scientific expeditions in the Alps made numerous experiments of the boiling temperature at different elevations. He found that the boiling temperature depends somewhat on the

(64) *U. S. Coast and Geodetic Survey, Report for* 1876, Washington, 1879, p. 367.

(65) *Philosophical Transactions*, Vol. 33, 1724, p. 179.

(66) *Mémoires de l'académie r. d. sciences*, année 1740.

depth of the water in the receptacle, that the boiling temperature reaches its maximum when the water boils with violence. Certain discordant results were laid to failure to make the tests under uniform conditions. He found that thermometric changes are not proportional to the corresponding barometric changes. The rate of change of the thermometric readings is less. But he was not able to deduce a workable formula. In 1775 Sir GEORGE SHUCKBURGH (67) repeated DE LUC's experiments and found that the boiling temperature does not drop quite as rapidly as DE LUC indicated. A theoretical study of this question was made by ANDREW URE (68) who measured the elastic force of water vapor. Supposing that the water boils at 212° F., when the barometer reads 30 inches, the water boils at 202° and 192° when the barometer reads $\frac{30}{1.23}$ and $\frac{30}{1.23 \times 1.24}$ inches respectively. The study of vapor pressure was taken up by F. J. H. WOLLASTON, (69) who introduced by interpolation much smaller intervals, making nine between 212° and 202° degrees. In a second table he gives boiling points and the corresponding elevations. Using a thermometer with a large tube specially designed for altitude determinations, in which the scale extended only a few degrees and a degree marked nearly 4 inches, so that, with a vernier, small fractions of a degree could be read, WOLLASTON determined the height of Snowden Hill to be 3546.25 feet by his thermometer, 3548.9 feet by the barometer, while General ROY's trigonometrical value was 3555.4 feet. The agreement was not so close on Moel Elio, which by his thermometer rose 2350.55 feet, by the barometer 2391.8 feet, by General ROY's trigonometric survey 2371 feet. Why the agreement should be so very much closer on Snowdon than on Moel Elio could not be discovered with certainty. WOLLASTON remarked that Snowden terminates in a point, while Moel Elio had a large base summit; moreover, the test on Moel Elio was made in a very high wind.

In more recent time HENRI VICTOR REGNAULT produced more exact tables of vapor tensions. After noting the vapor tension, the computations for fixing altitudes are the same as when a

(67) *Philosophical Transactions*, Vol. 69, for the year 1779, p. 363.
(68) *Phi osophical Transactions*, Vol. 108, 1818, p. 338.
(69) *Philosophical Transactions*, Vol. 110, 1820, p. 295, 302.

barometer is employed. REGNAULT constructed a small instrument for thermometric height determinations which he called the hypsometer. For approximate results, a formula due to SORET may be used, $h = 295\ (100 - t)$, where h is expressed in meters, t in degrees centigrade.

Later results. An idea of the accuracy due to later improvements is afforded by measurements at Mount Washington in New Hampshire, the height of which had been determined by the U. S. Coast Survey in its primary triangulation, to be 6288 feet (1917 m.). For the purpose of comparing methods, this height was divided, in 1854, into steps of about 500 feet difference in elevation, thus forming 12 stations, at which T. J. CRAM (70), who was in charge of secondary triangulation, took simultaneous observations (« in the same minute ») by the barometric and the boiling point method. The difference in elevation of two of the stations which was 6280 feet by the process of leveling, was found to be 6206 feet by the barometer, and 6116 feet by the boiling point. CRAM states that « the results given by the barometer, however erratic they may seem, wander less from those by the leveling instrument than do the results given by the thermo-barometric boiling-point apparatus. » He states that whatever error in the barometric method may be attributed to the constants in the barometric formula, will likewise be found in the results of the thermometric method, as this formula is used in both instruments.

University of California. FLORIAN CAJORI.

(70) *U. S. Coast Survey, Report* for 1854, p. 102*, 103*.

Index of Authors to Volumes X, XI and XII

Indices to *Isis* have appeared in Vol. I and in subsequent volumes of wich the ordinal number is divisible by three. I would advise readers to put some mark (e.g. the word index) on the backs of the volumes containing an index.

Special pains have been taken to include in this index, as in the previous one, the names of every person about whom some information may be found. Casual references have been omitted.

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